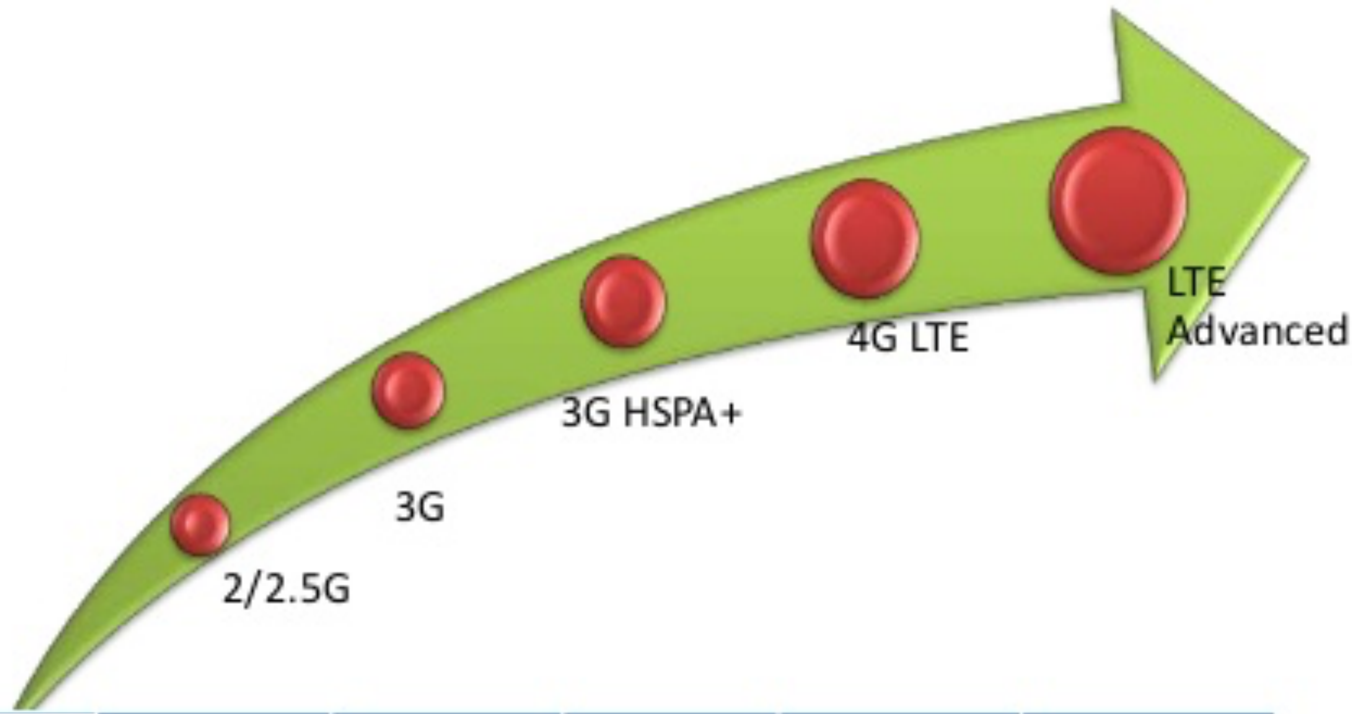
Massive MIMO Full-duplex: Theory and Experiments

Ashu Sabharwal

Joint work with **Evan Everett, Clay Shepard and Prof. Lin Zhong**

RICE
Electrical and Computer Engineering

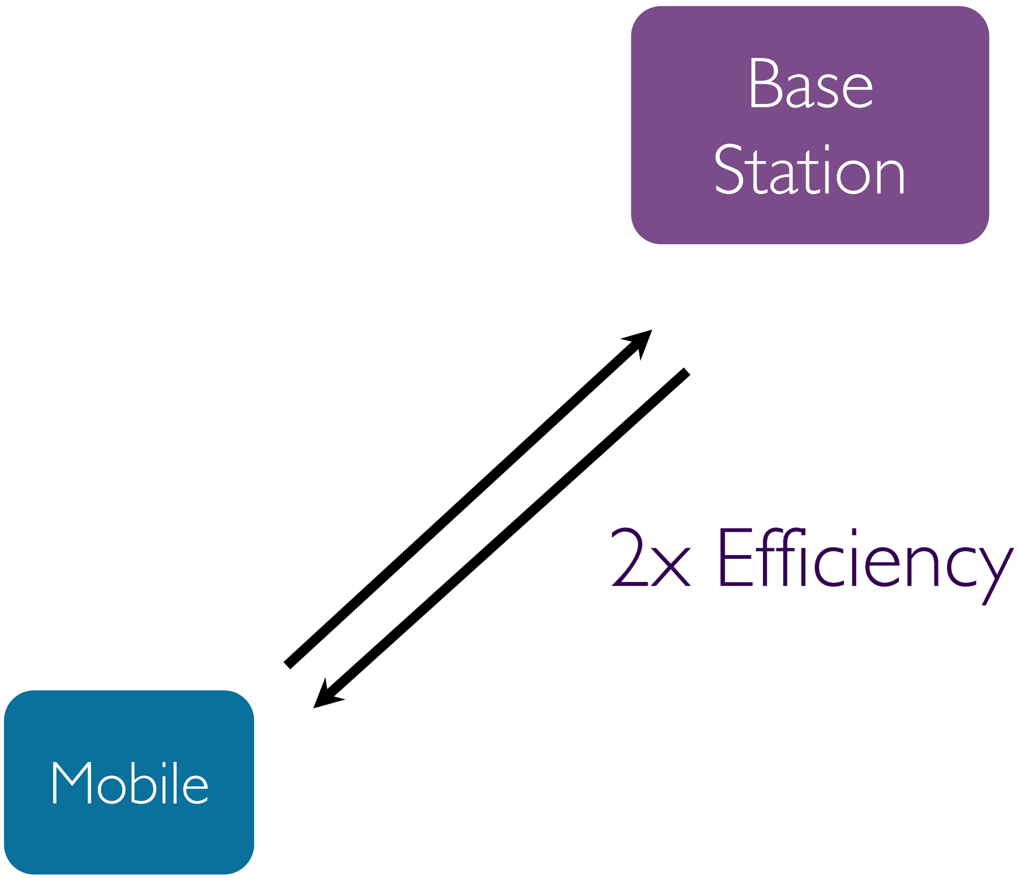
Data Rate Through Generations



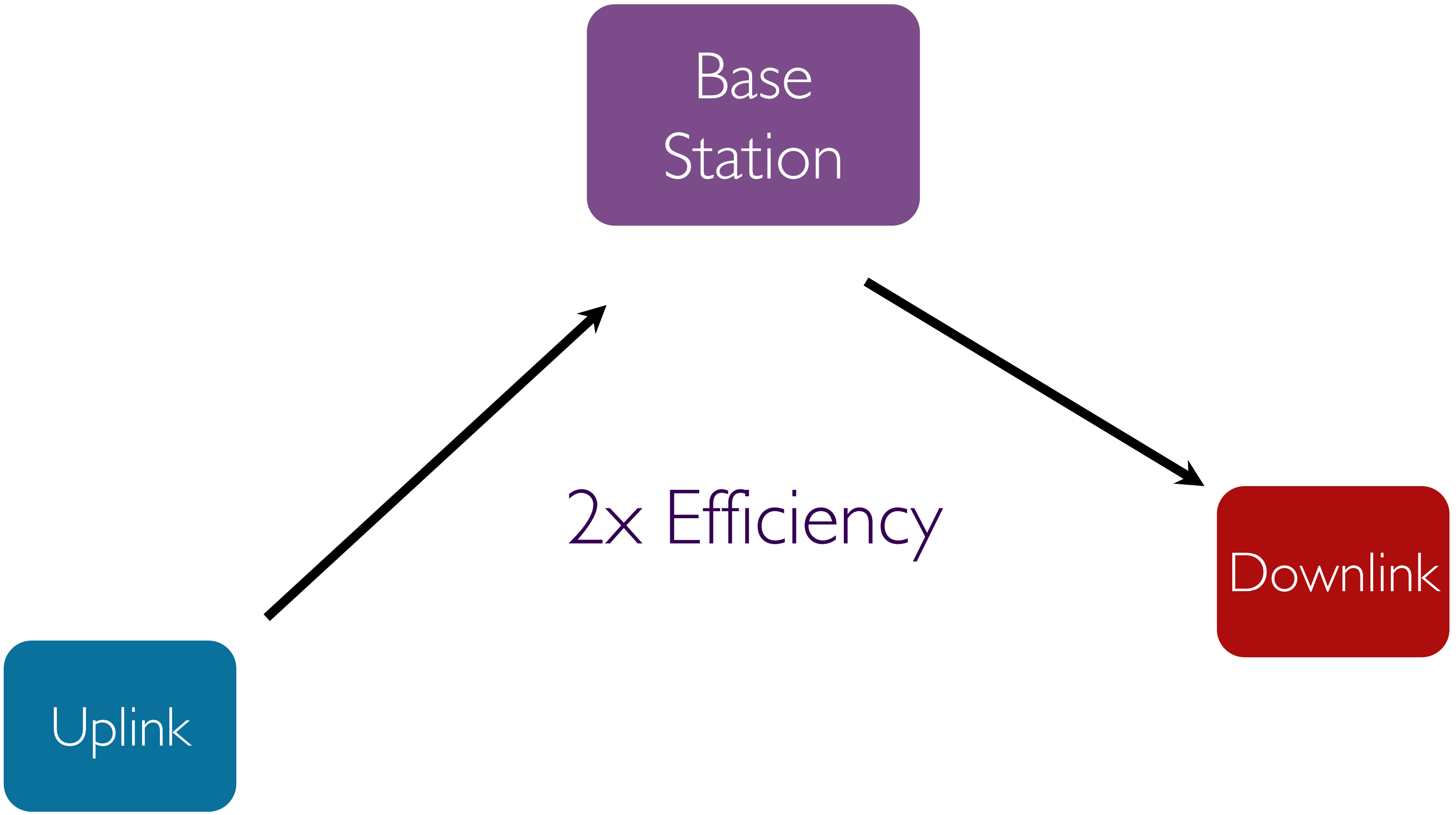
	2000	2006	2009	2010	2016
Peak Rate	172 kbps	7 Mbps	42 Mbps	~150 Mbps	~1 Gbps

Gains from Spectrum, Densification & <u>Spectral Efficiency</u>

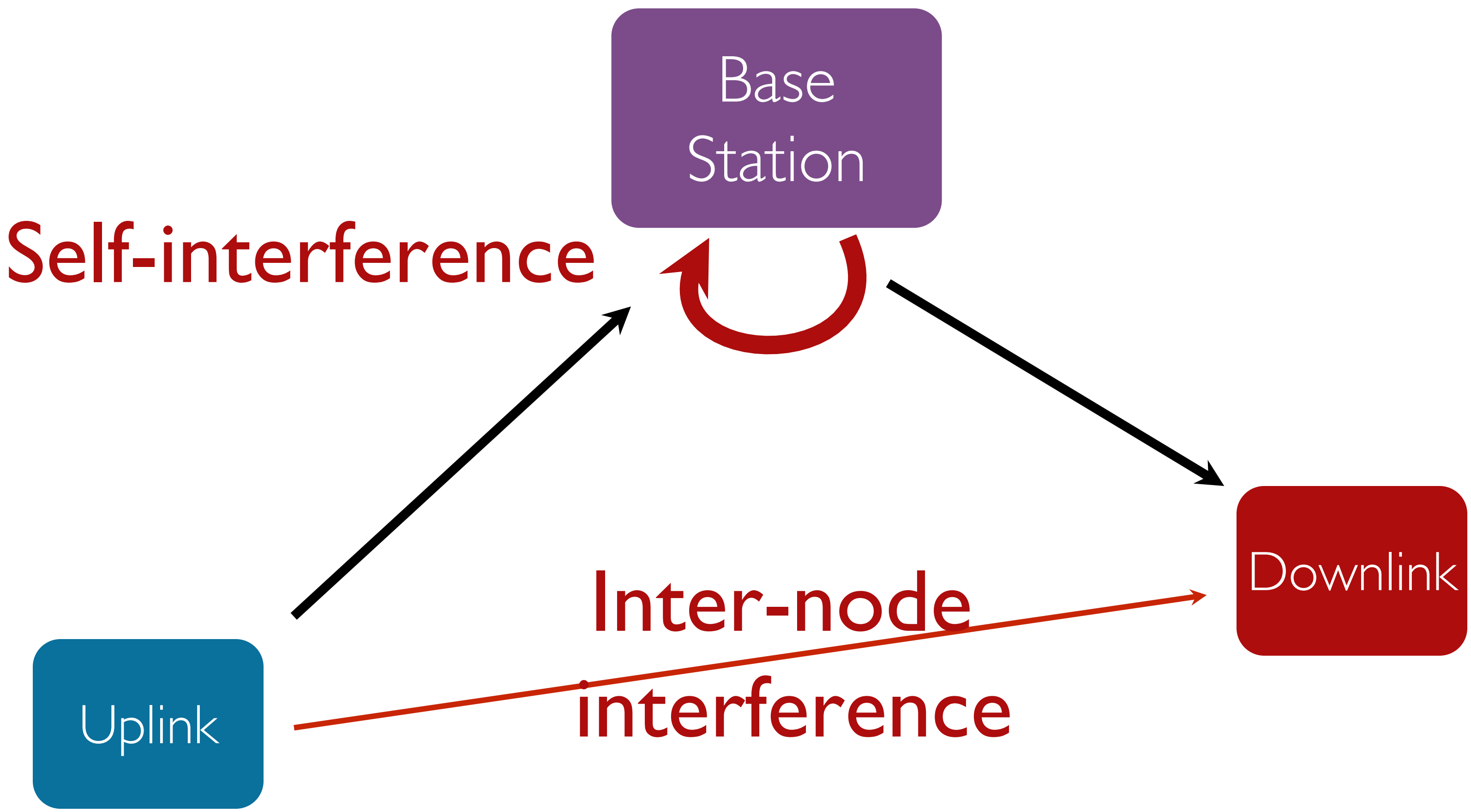
In-band Full-duplex Wireless



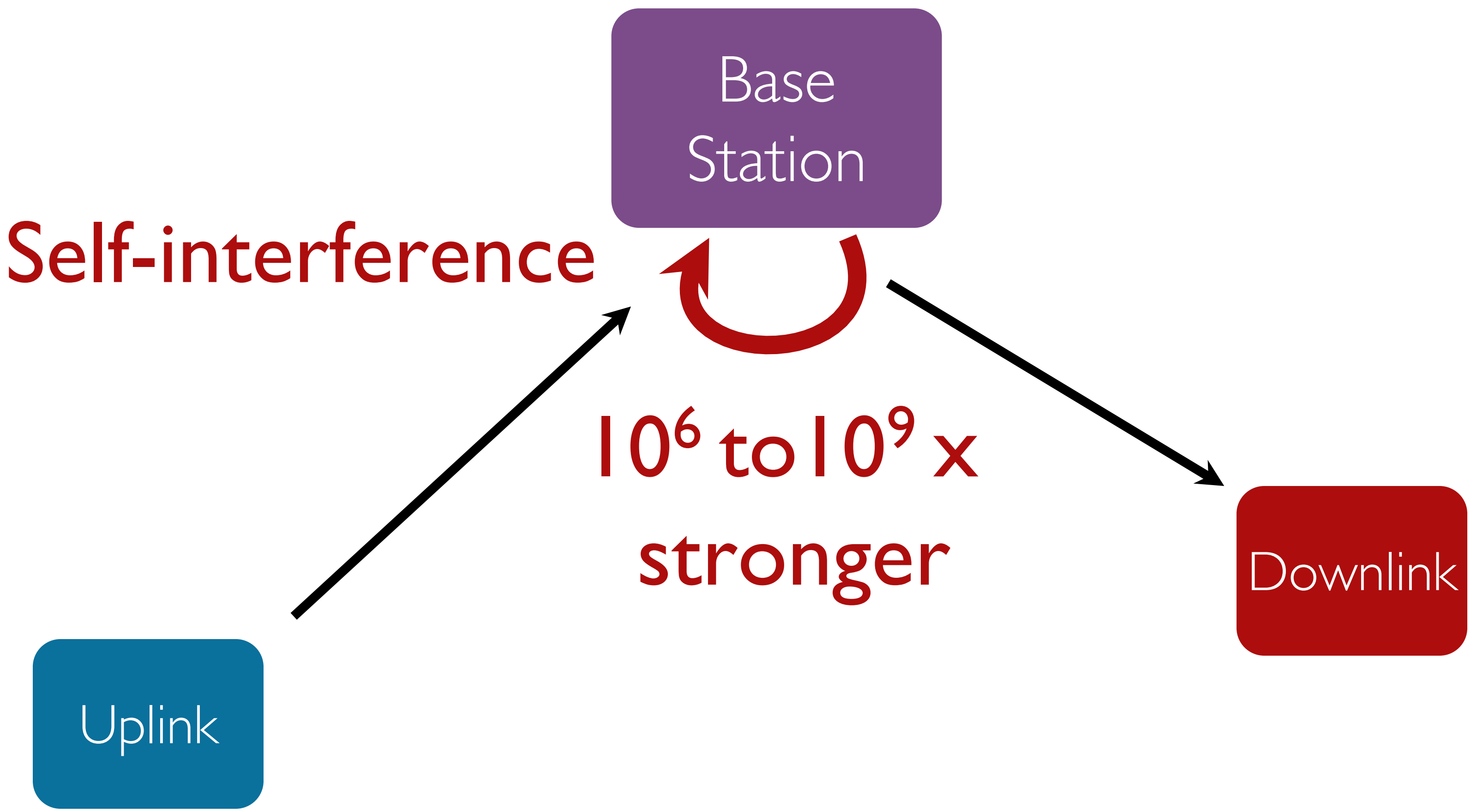
In-band Full-duplex Wireless



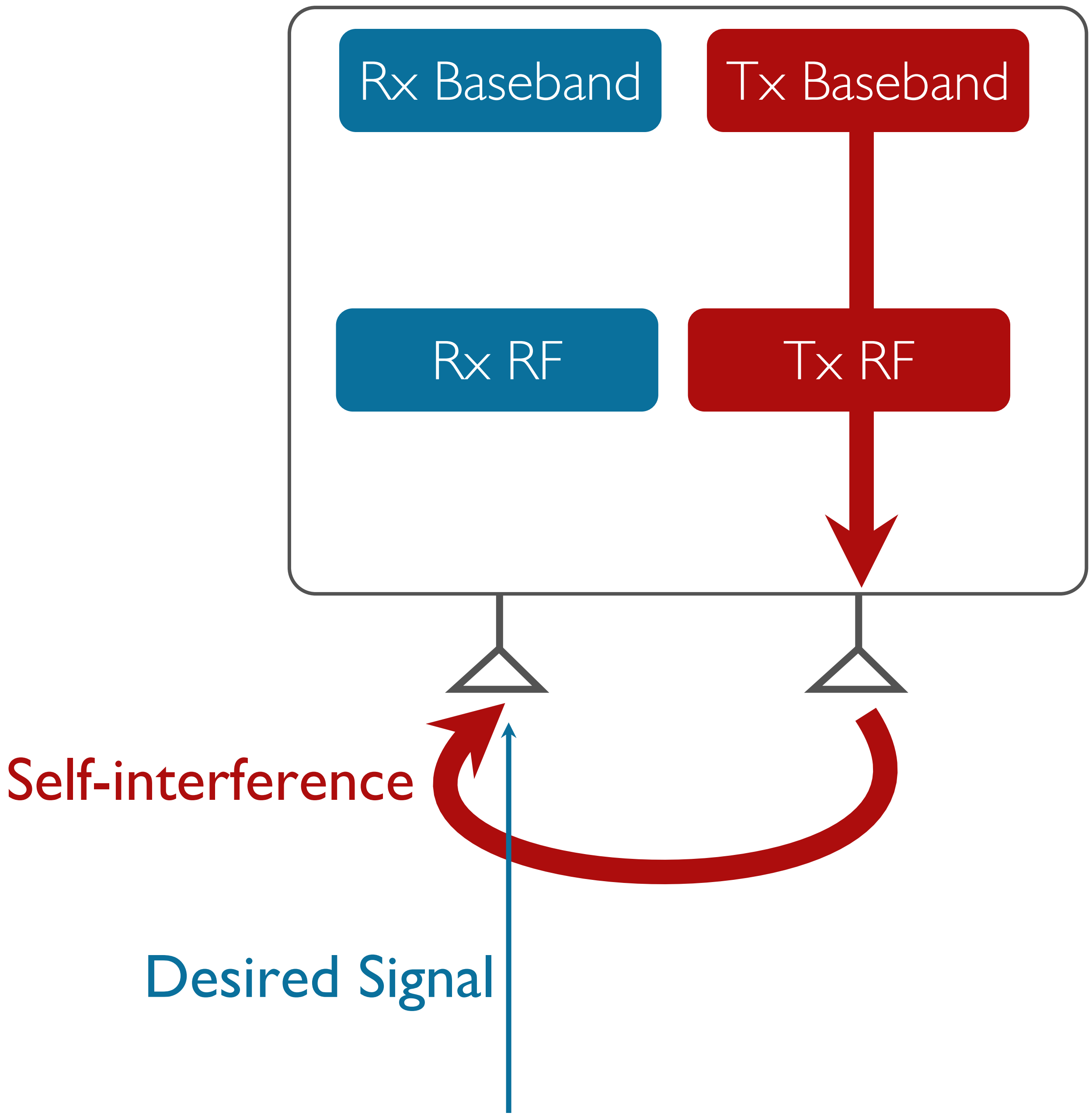
Full-duplex Wireless: Two Main Interferences



Full-duplex Wireless: Focus on Self-Interference



Self-interference bottleneck



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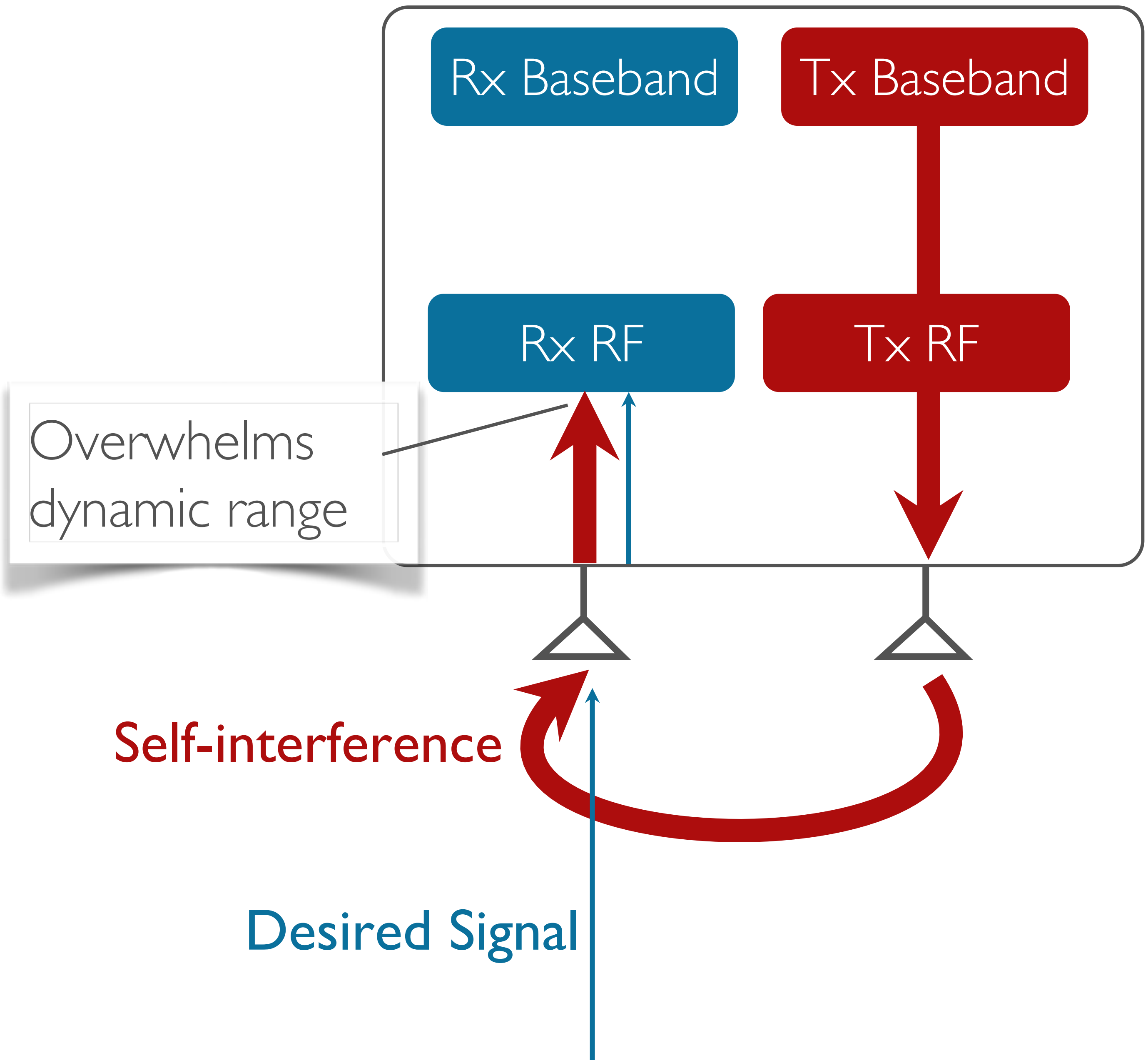

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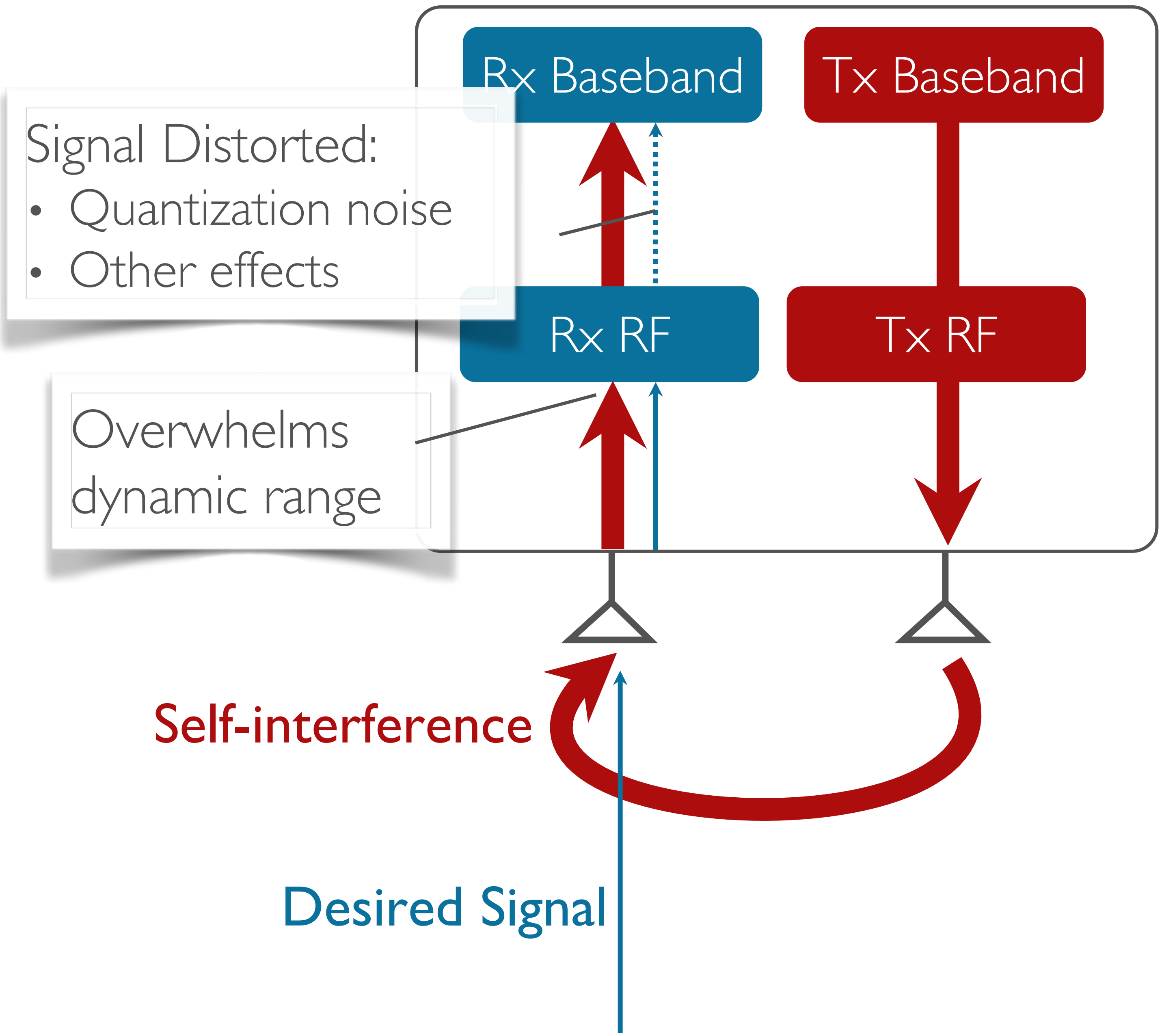
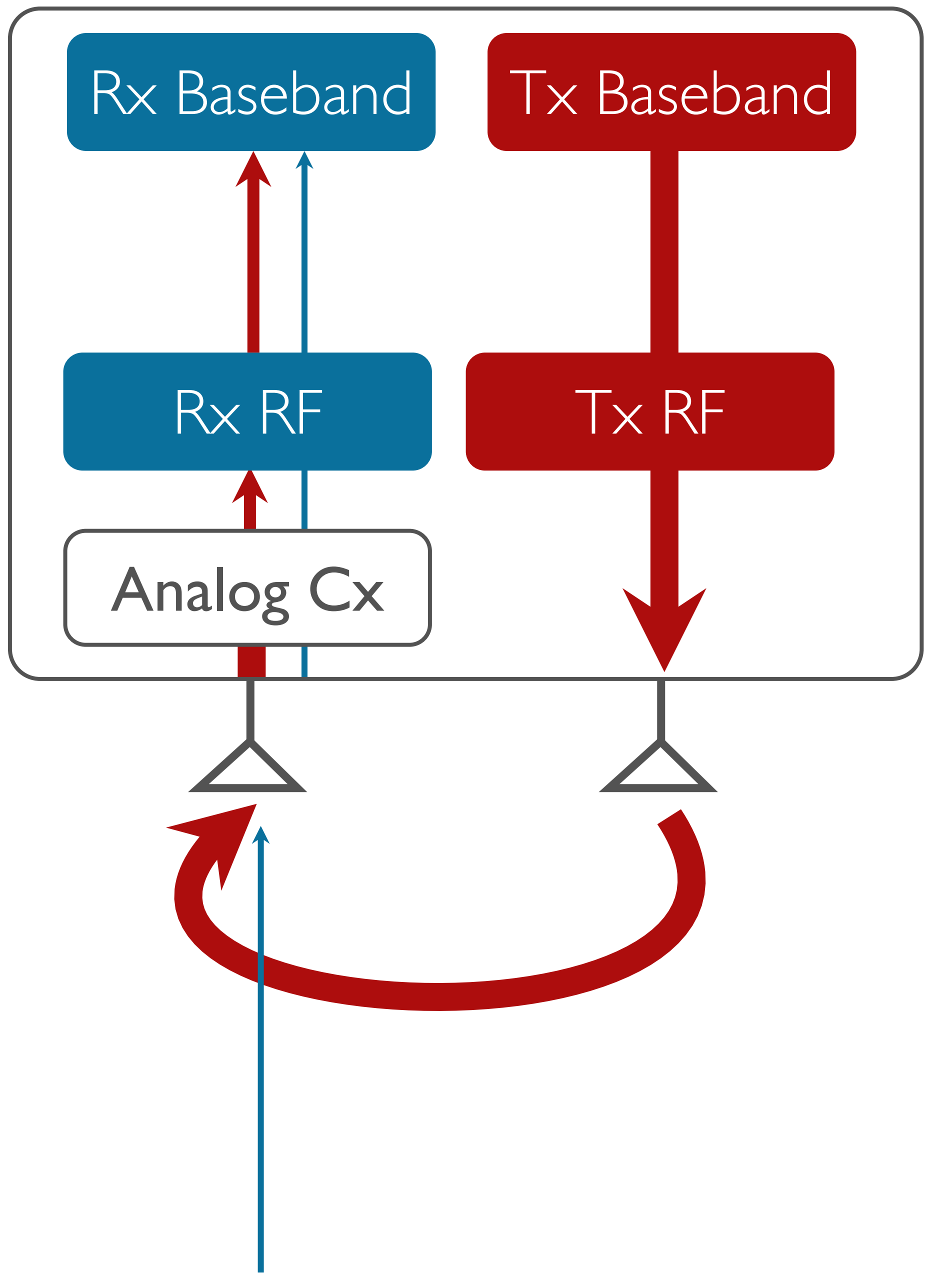
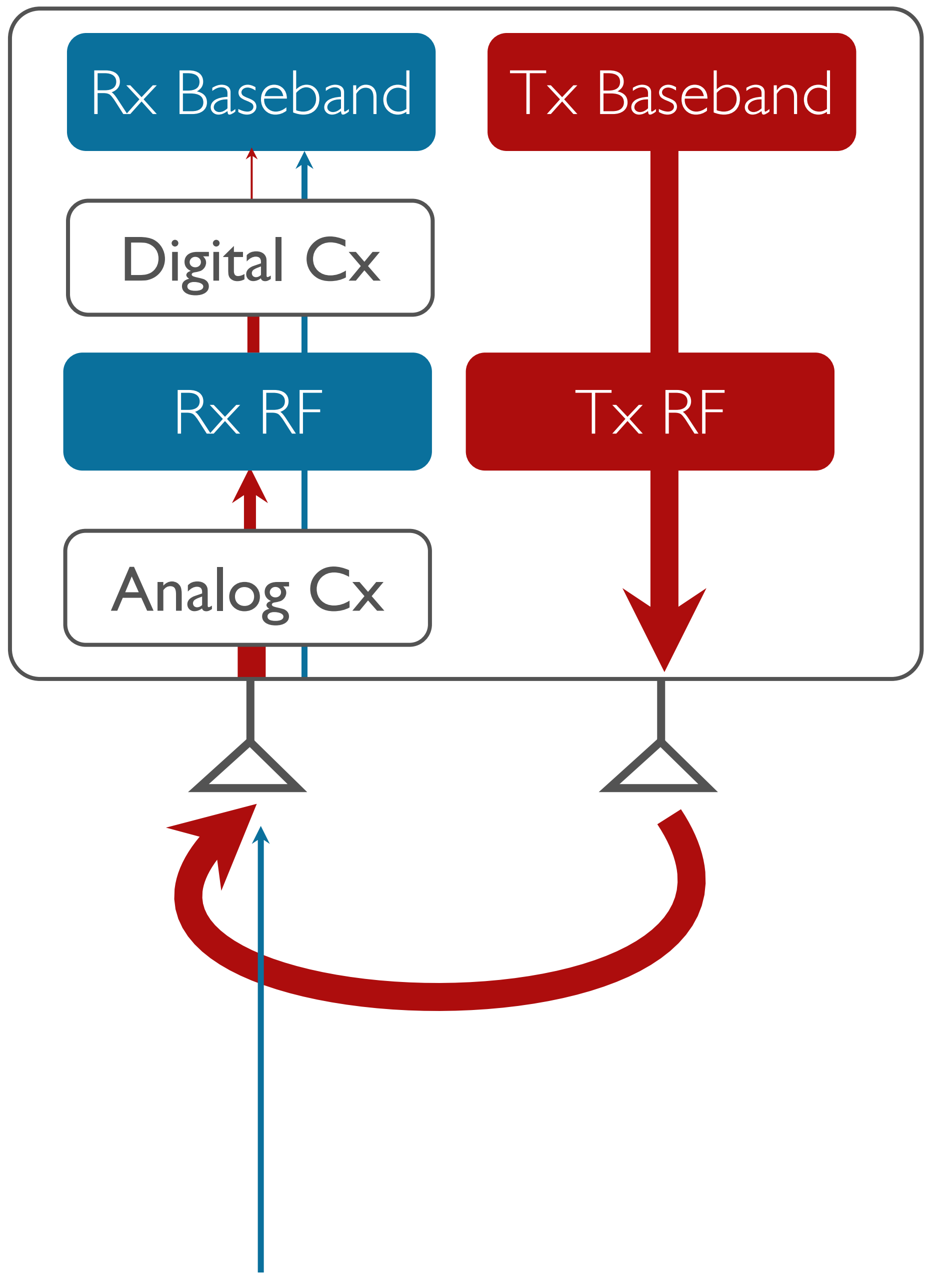


Self-interference suppression



Self-interference suppression



Two Experimental Demonstrations in 2010

Achieving Single Channel, Full Duplex Wireless Communication

Jung Il Choi[†], Mayank Jain[†], Kannan Srinivasan[†], Philip Levis, Sachin Katti
Stanford University
California, USA
{jungilchoi,mayjain,srikank}@stanford.edu, pal@cs.stanford.edu, skatti@stanford.edu
[†]Co-primary authors

Full-Duplex Wireless Communications Using Off-The-Shelf Radios: Feasibility and First Results

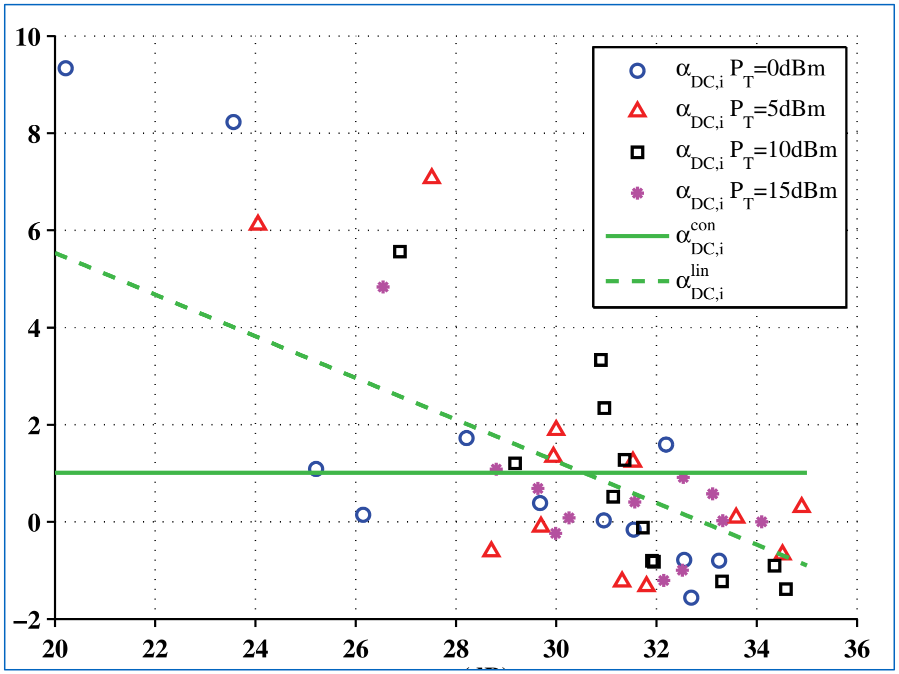
Melissa Duarte and Ashutosh Sabharwal
Department of Electrical and Computer Engineering, Rice University, Houston, TX 77005
Email: {mduarte, ashu}@rice.edu

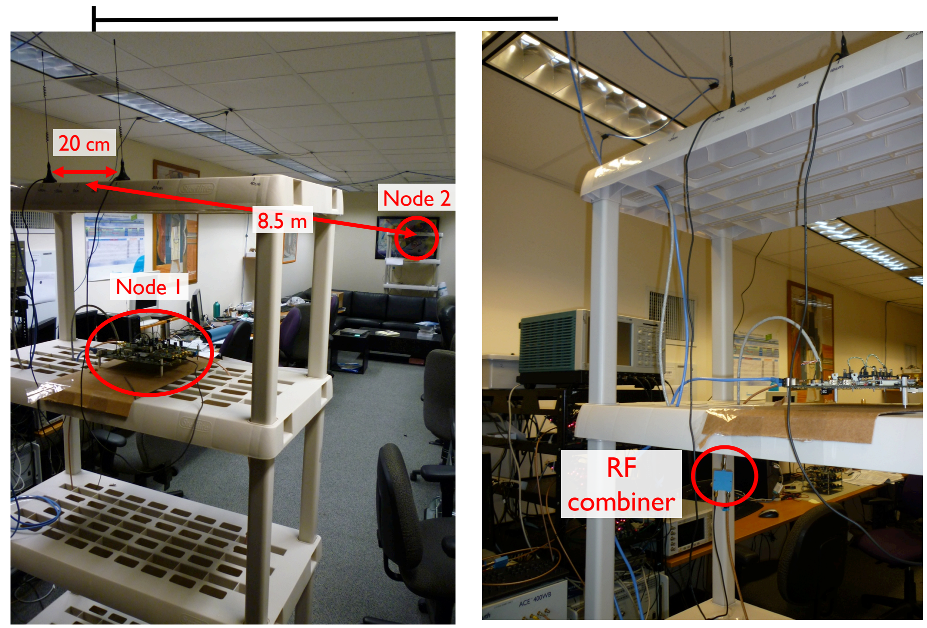
Lots of *well-deserved* skepticism

Identifying The Bottlenecks

Experiment-Driven Characterization of Full-Duplex Wireless Systems

Melissa Duarte, Chris Dick, and Ashutosh Sabharwal



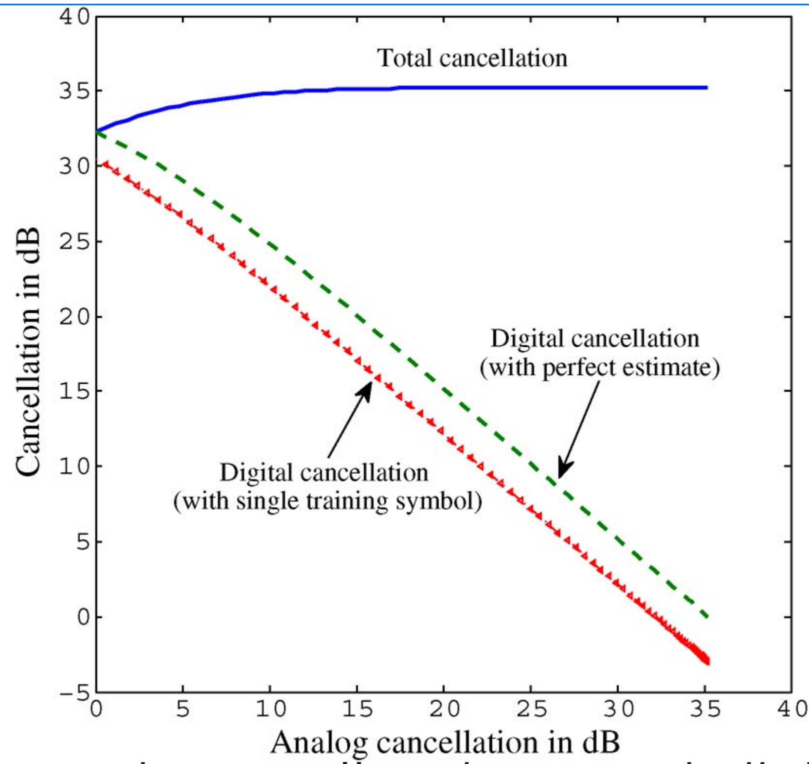


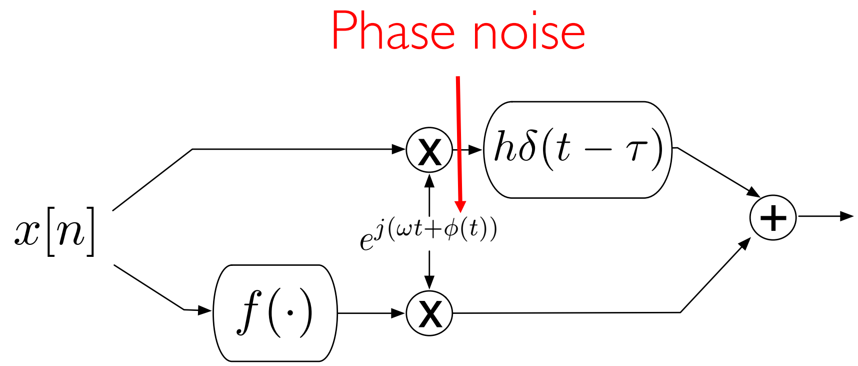
- Experimentally observed digital & analog cancellation is not additive, and in fact, inversely related

Identifying The Bottlenecks

On the Impact of Phase Noise on Active Cancelation in Wireless Full-Duplex

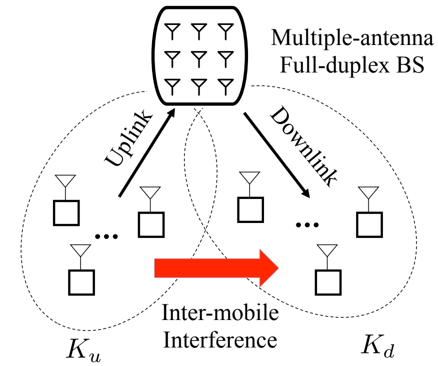
Achaleshwar Sahai, Gaurav Patel, Chris Dick, and Ashutosh Sabharwal, *Senior Member, IEEE*





- Experimentally observed digital & analog cancellation is not additive, and in fact, inversely related
- Culprit was transmitter phase noise, explained all our results

Practical Protocols with Experimental Demonstrations



IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 14, NO. 7, JULY 2015

Power-Controlled Medium Access Control Protocol for Full-Duplex WiFi Networks

Wooyeol Choi, Hyuk Lim, *Member, IEEE*, and Ashutosh Sabharwal, *Fellow, IEEE*

2015

IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 15, NO. 12, DECEMBER 2016

Sequential Beamforming for Multiuser MIMO With Full-Duplex Training

Xu Du, John Tadrous, *Member, IEEE*, and Ashutosh Sabharwal, *Fellow, IEEE*

2016

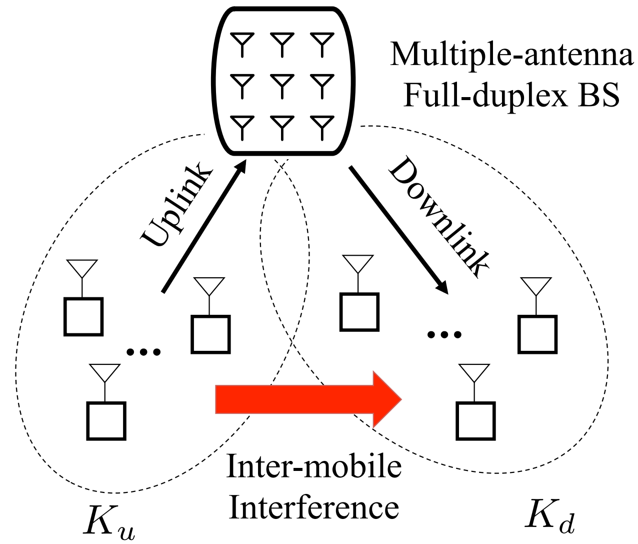
IEEE/ACM TRANSACTIONS ON NETWORKING

Leveraging One-Hop Information in Massive MIMO Full-Duplex Wireless Systems

Wenzhuo Ouyang, *Member, IEEE*, Jingwen Bai, and Ashutosh Sabharwal, *Fellow, IEEE*

2017

Impact on Network Capacity



On Degrees-of-Freedom of Full-Duplex Uplink/Downlink Channel

Achaleshwar Sahai, Suhas Diggavi and Ashutosh Sabharwal

2013

On Uplink/Downlink Full-Duplex Networks

Achaleshwar Sahai, Suhas Diggavi and Ashutosh Sabharwal

2013

On Degrees-of-Freedom of Multi-User MIMO Full-Duplex Network

Jingwen Bai
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Ashutosh Sabharwal
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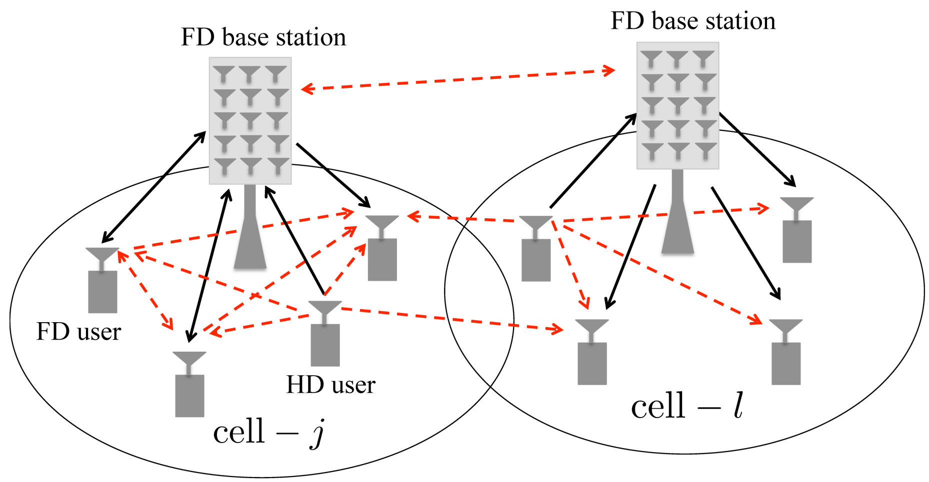
2015

Multi-cell Analysis Promises Spectral Efficiency Gains



Asymptotic Analysis of MIMO Multi-Cell Full-Duplex Networks

Jingwen Bai and Ashutosh Sabharwal, *Fellow, IEEE*

2017

- Network throughput gains, even with errors, half-duplex nodes and increased interference
- Asymptotically spectral efficiency approaches 2X
- With 64-256 antenna gains approaches 1.8X (5G array sizes)

Full-duplex in Wireless and Wireline

- 3GPP full-duplex backhaul

Deutsche Telekom completes 5G full duplex field trial with Kumu Networks

FierceWireless, Sept'15

- Cable Labs: next-gen cable modems

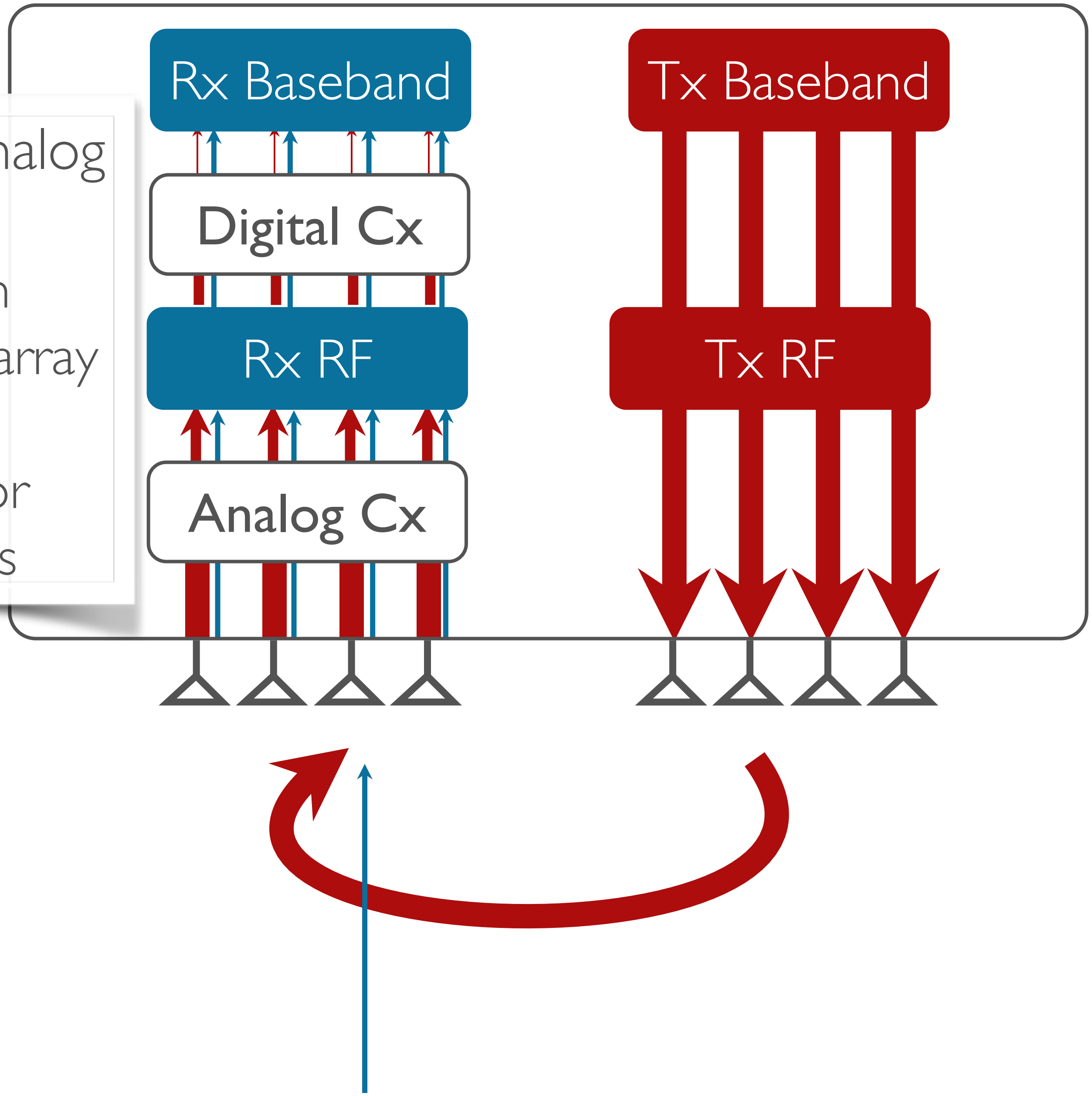
Full Duplex DOCSIS® 3.1 Technology: Raising the Ante with Symmetric Gigabit Service

CableLabs, Feb'16

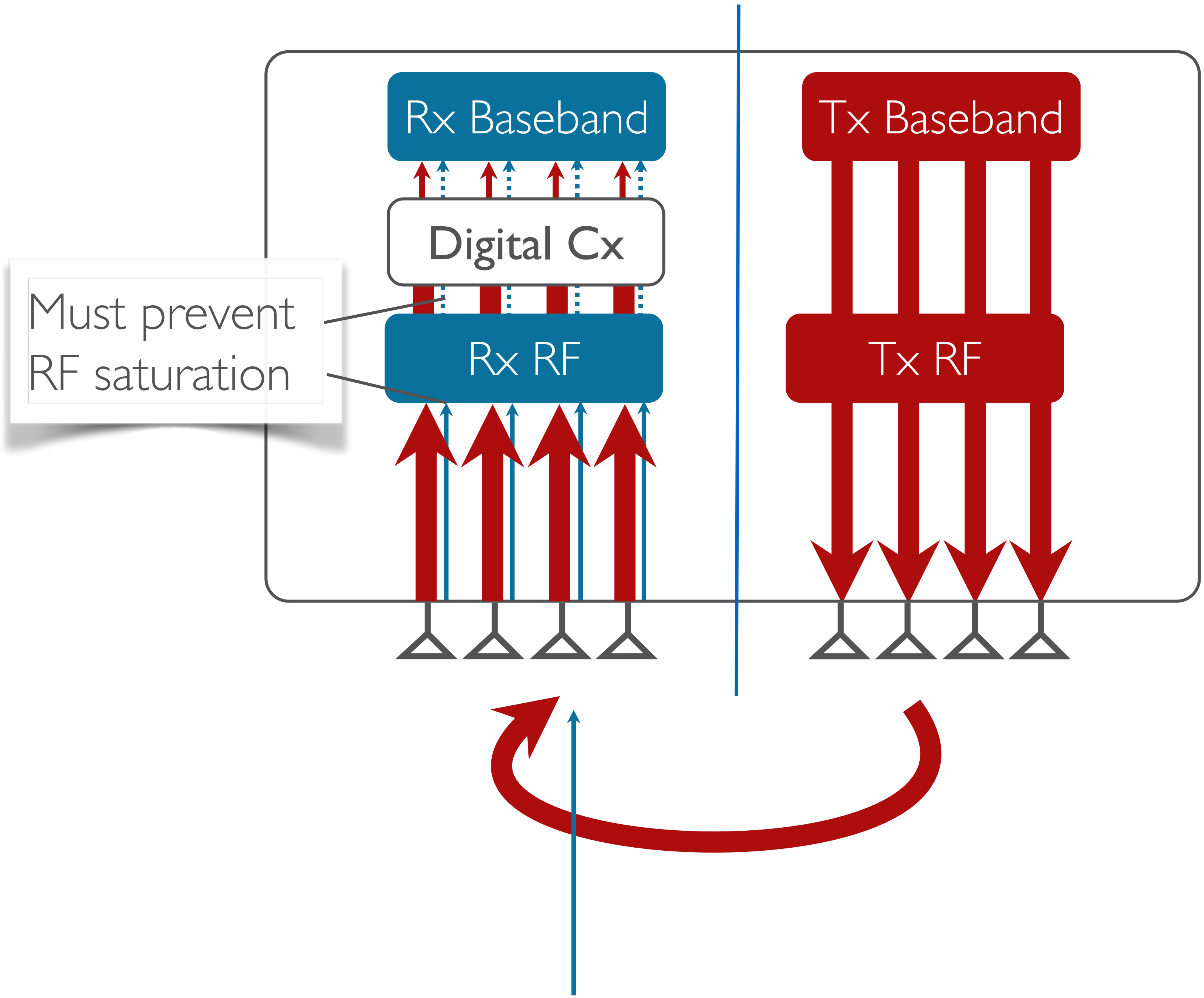
New Headache – Too Much Analog !

Complex analog circuitry

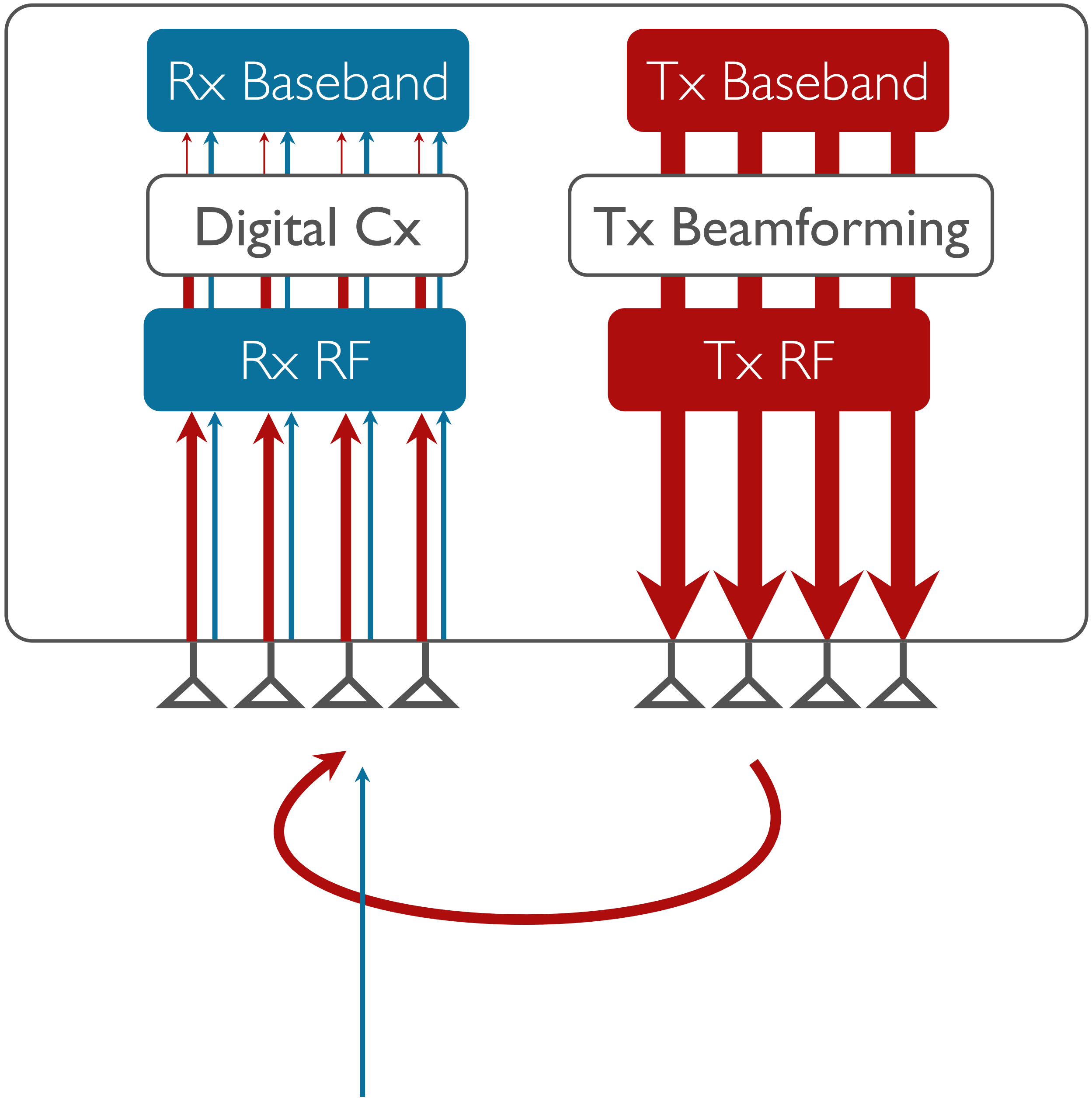
- Scales with square of array size
- Ill-suited for large arrays



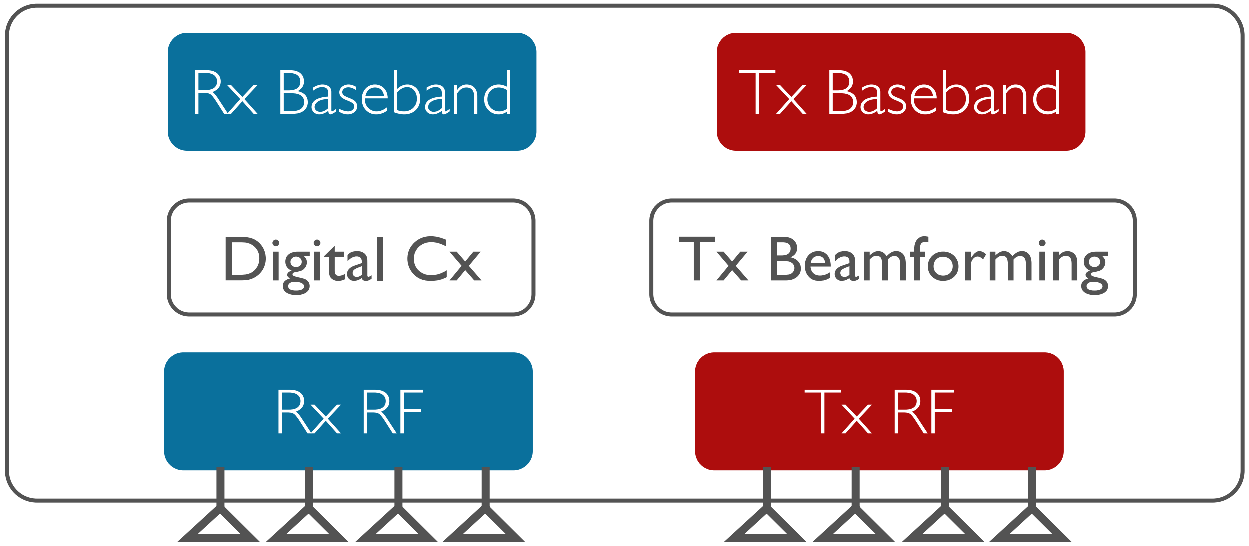
“All-digital" Full-duplex (no new analog) ?



Goal: All-digital Full-duplex Architecture via Beamforming

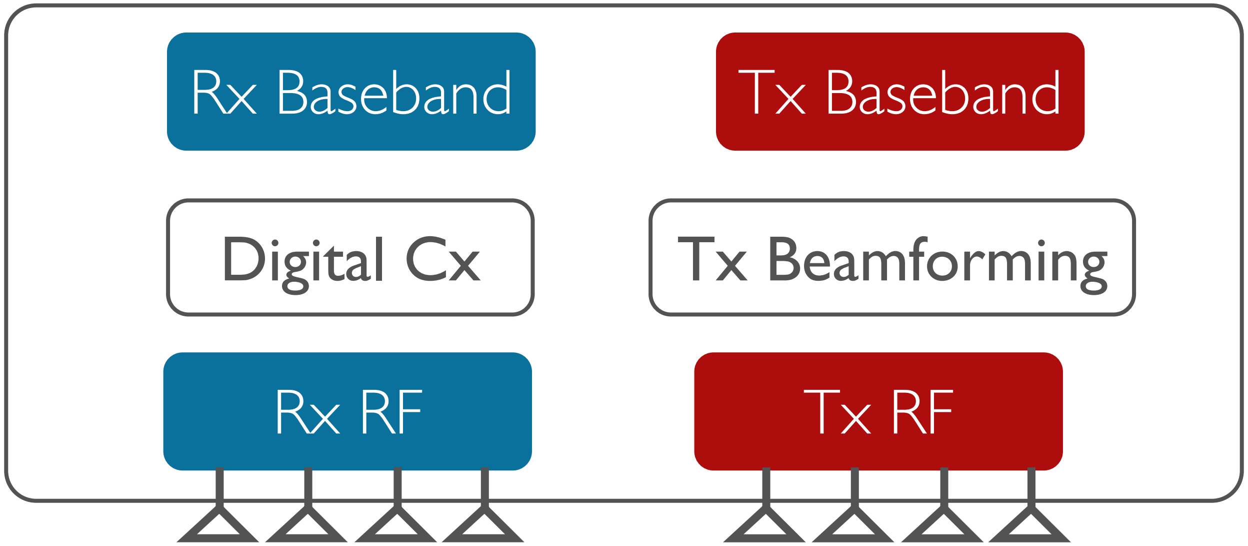


Questions to Answer



1. In what conditions is all-digital FD feasible?
2. What are practical algorithms for all-digital FD?

Questions to Answer



1. In what conditions is all-digital FD feasible?

Answer with info-theoretic analysis

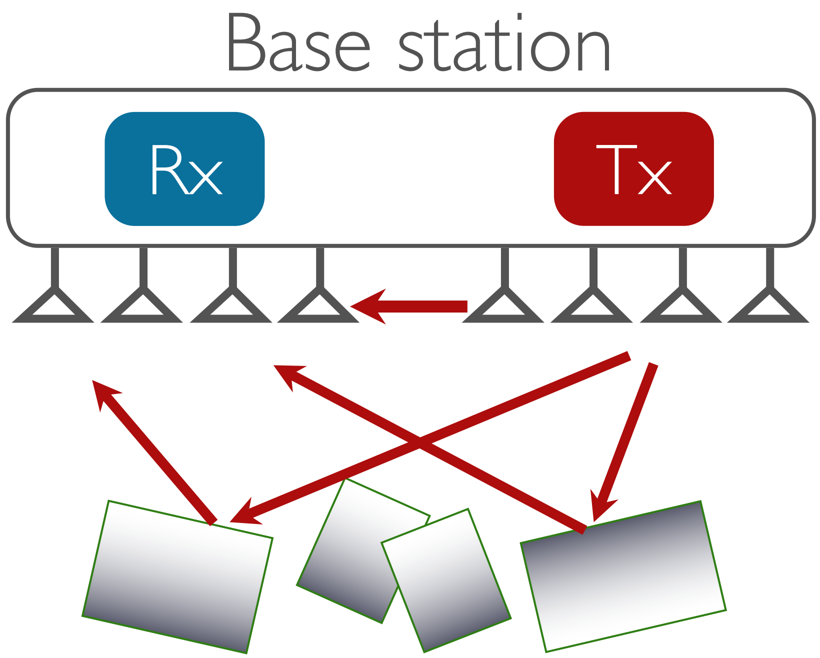
2. What are practical algorithms for all-digital FD?

Answer with design and experiment

Components of Self-Interference

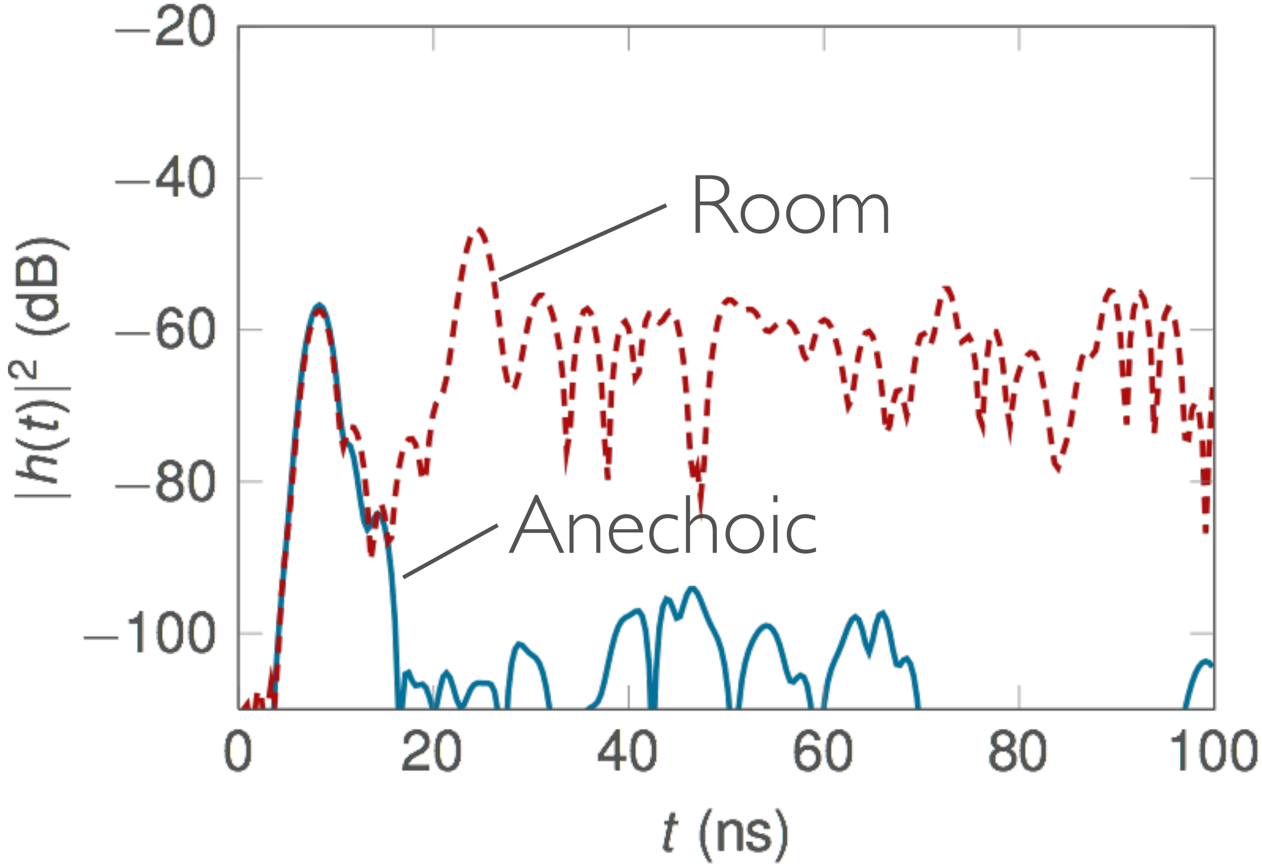
Direct-path

Backscattered



Everett, Sahai and Sabharwal "Passive Self-interference Suppression For Full-duplex Infrastructure Nodes" in IEEE Trans. Wireless Comm, 2014.

Experimental Evidence for Backscattering



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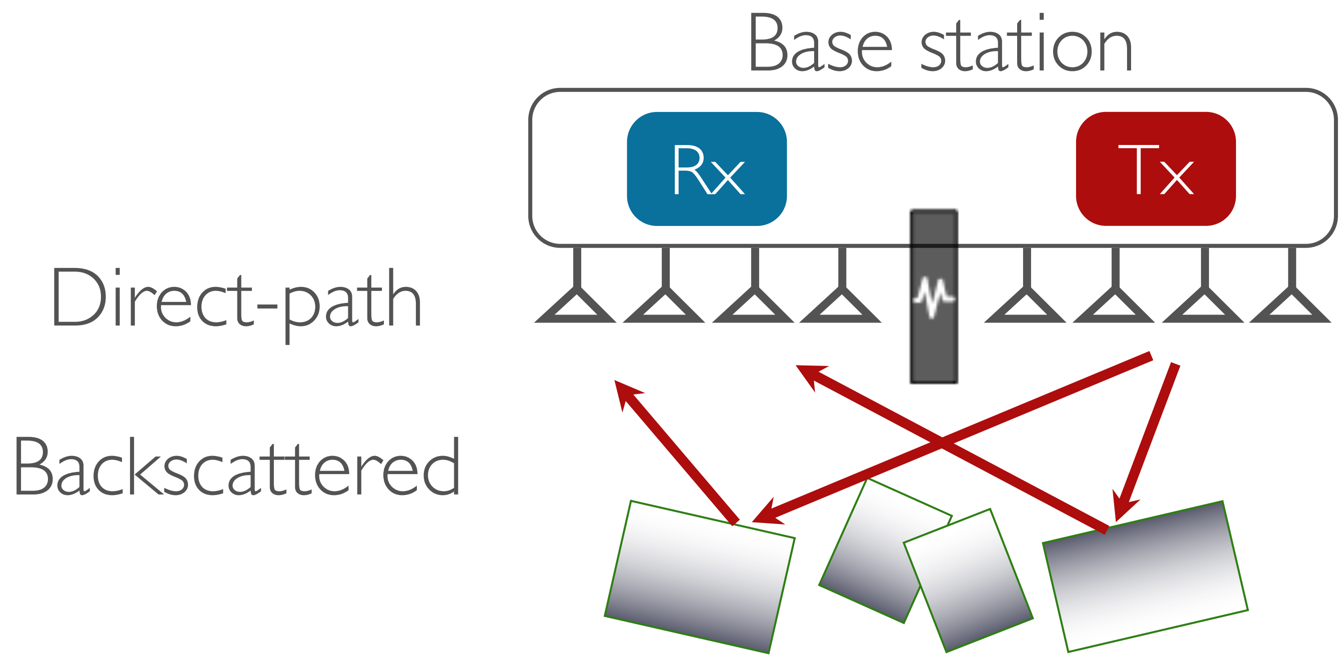
The Challenge of Backscattering



Direct-path can be passively suppressed

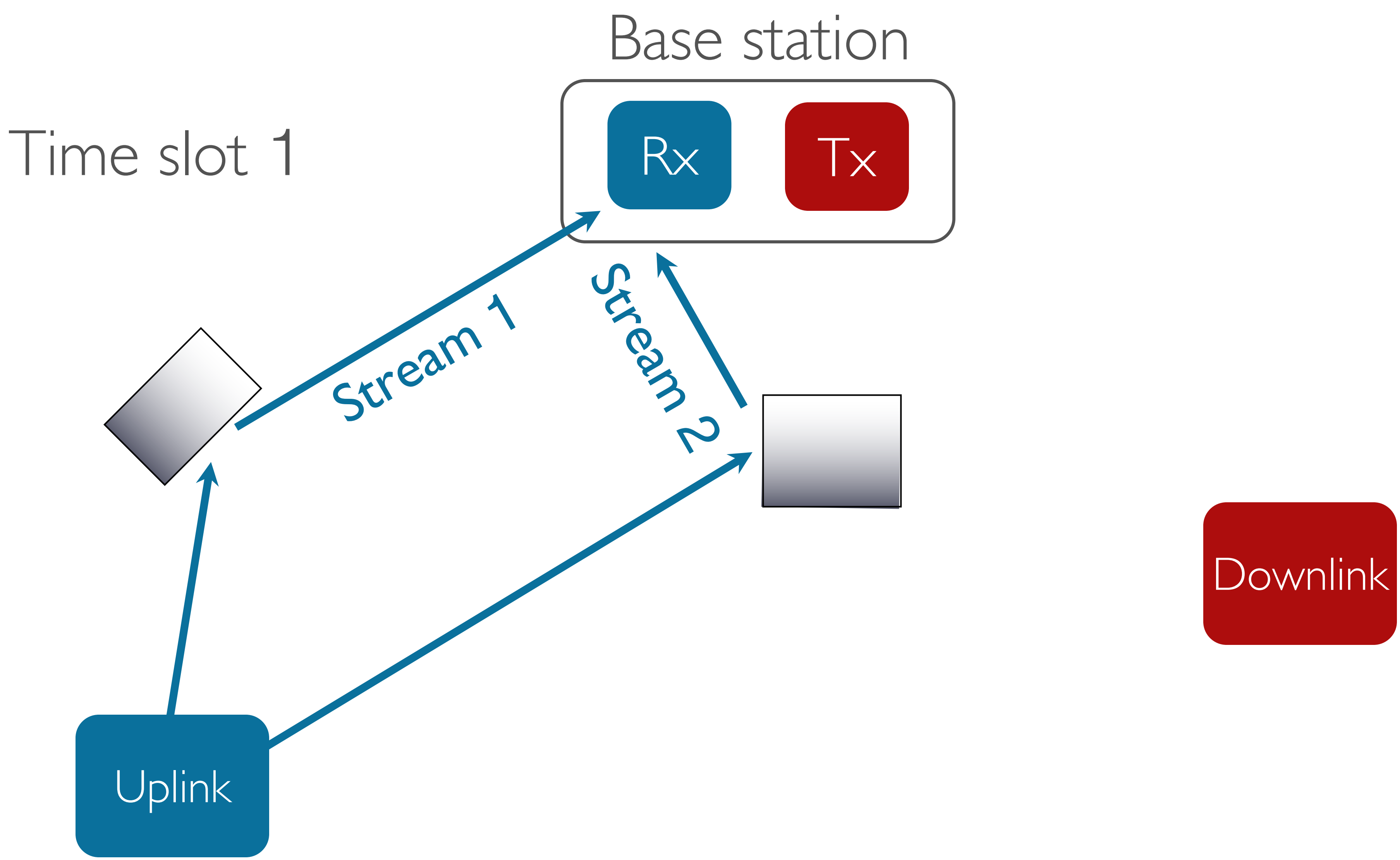
Backscattering becomes bottleneck

Everett, Sahai and Sabharwal "Passive Self-interference Suppression For Full-duplex Infrastructure Nodes" in IEEE Trans. Wireless Comm, 2014.

Can we do a better job of spatial isolation in a backscattering environment?

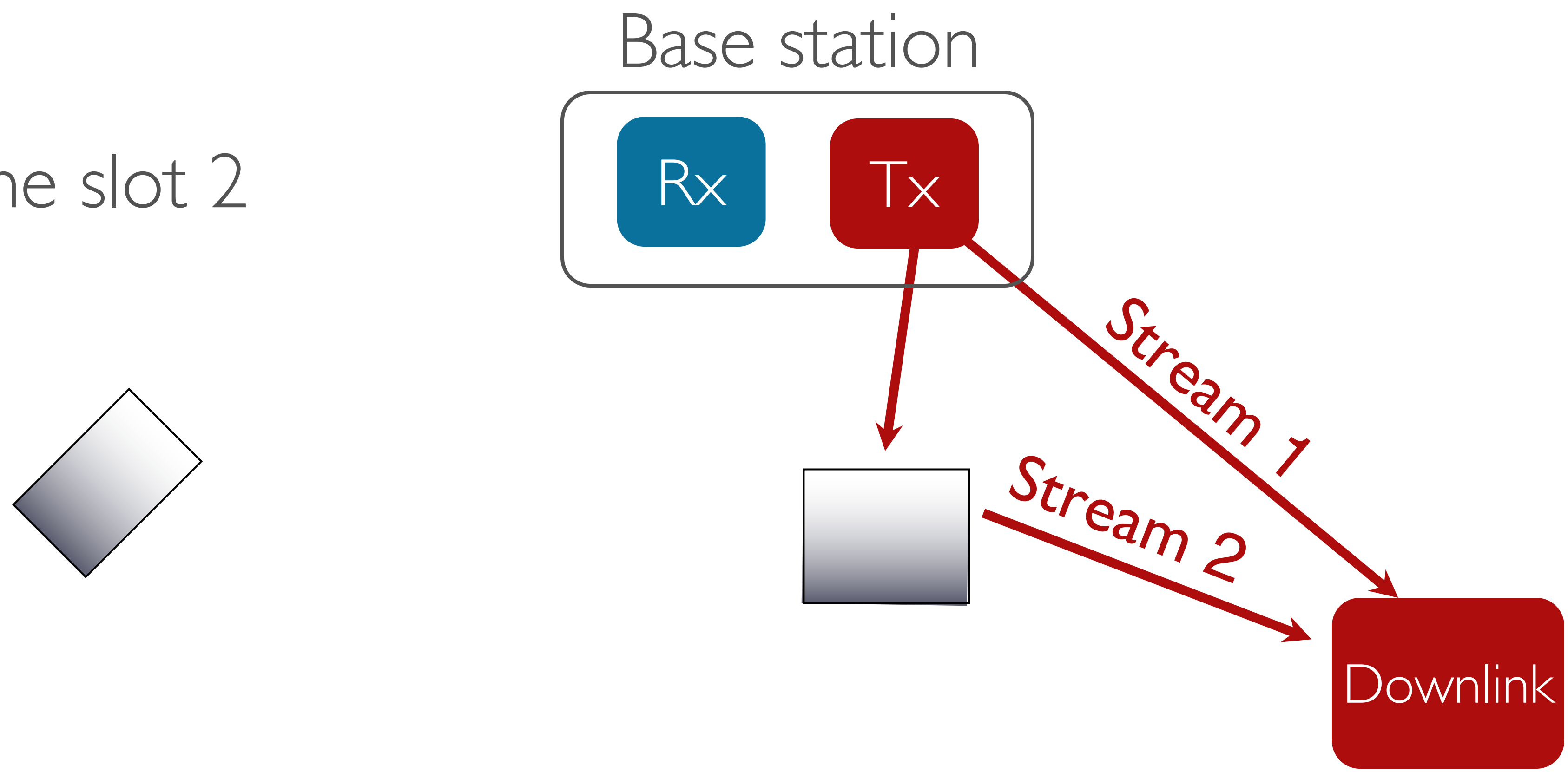
Yes, but there is a catch !

Half-duplex Spatial Multiplexing



Half-duplex Spatial Multiplexing

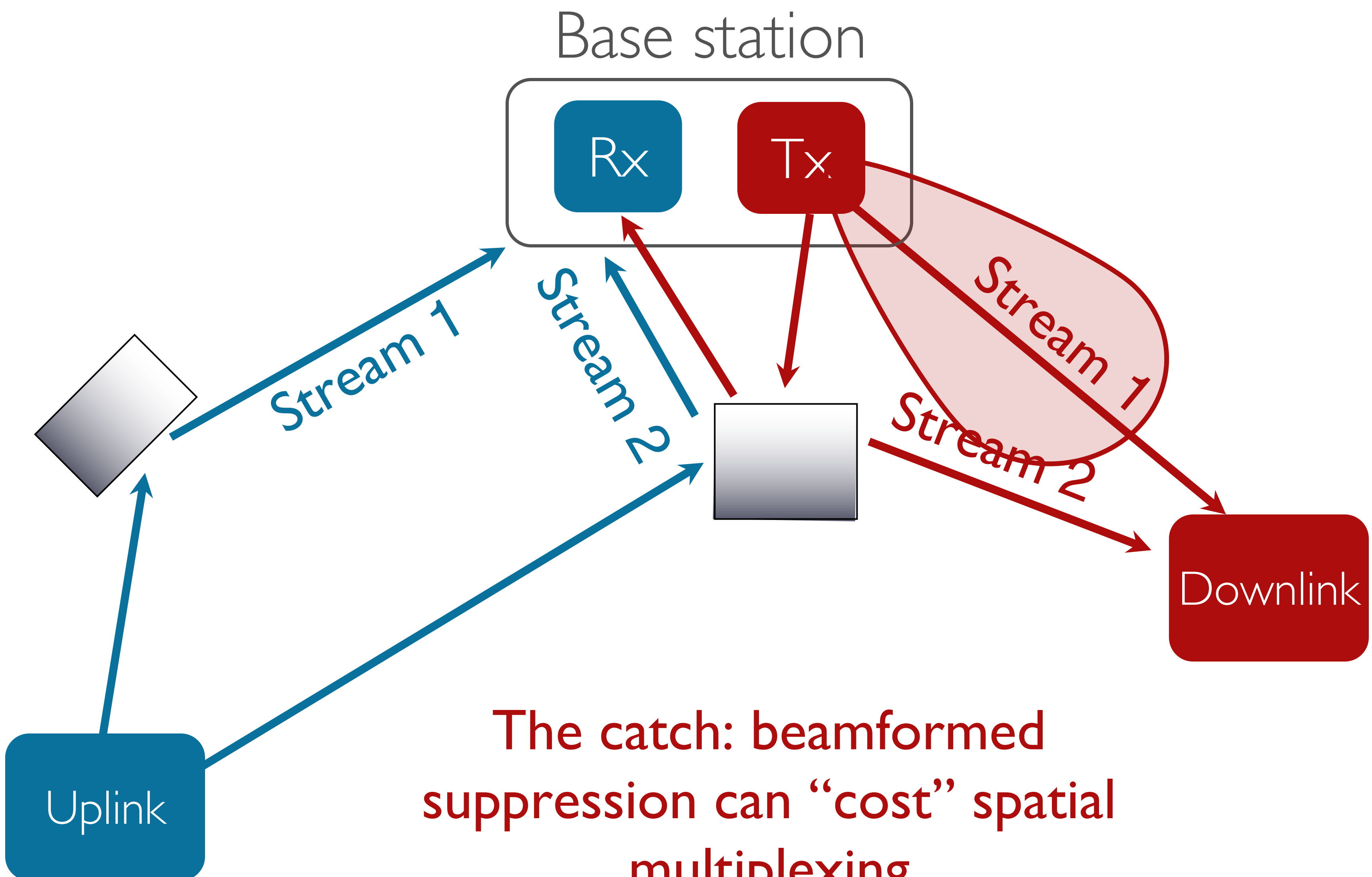
Time slot 2



$$\text{Uplink DoF} = \frac{\text{2 data streams}}{\text{2 time slots}} = 1$$

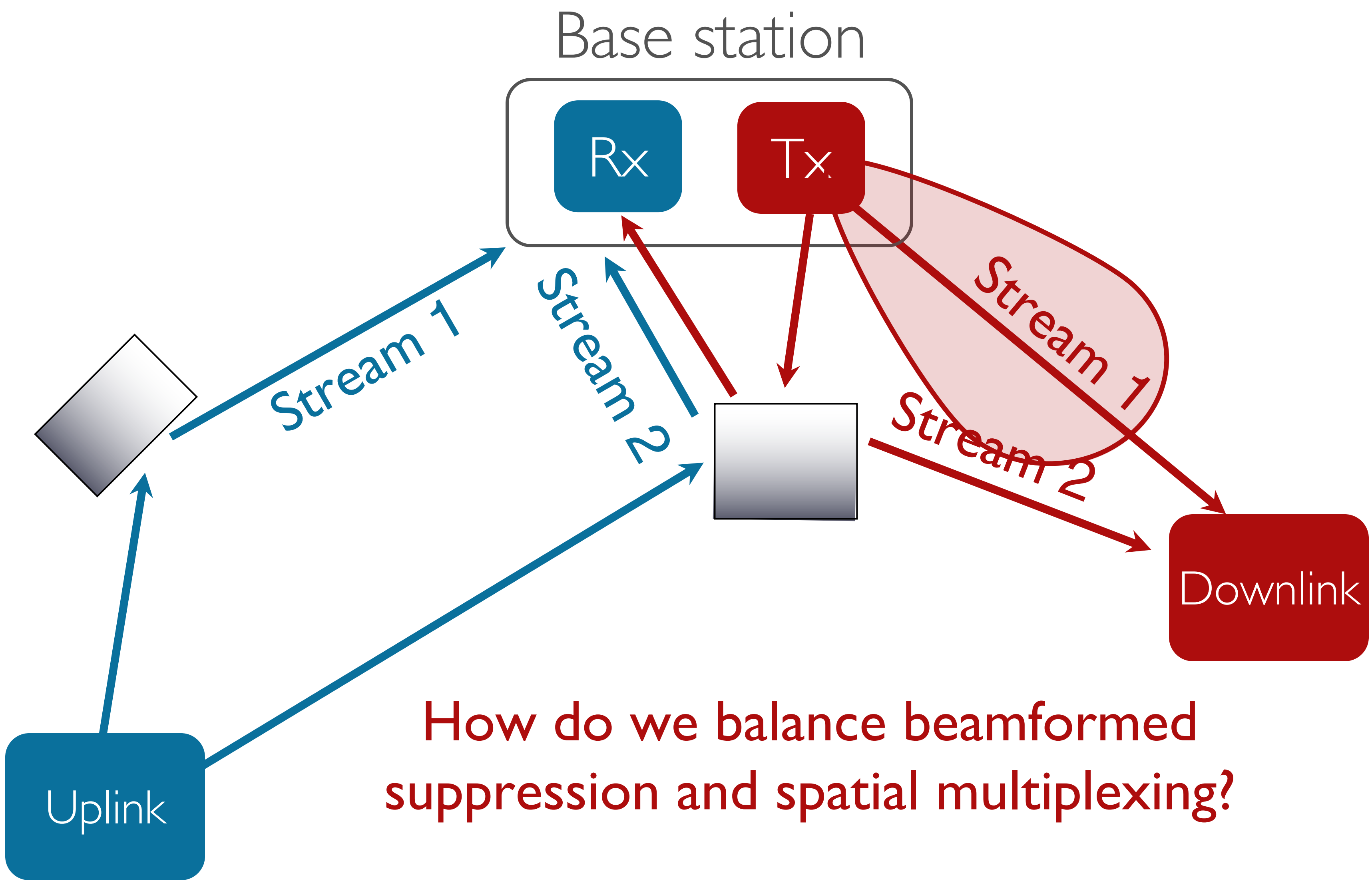
$$\text{Downlink DoF} = \frac{\text{2 data streams}}{\text{2 time slots}} = 1$$

Full-duplex Spatial Multiplexing



The catch: beamformed suppression can "cost" spatial multiplexing

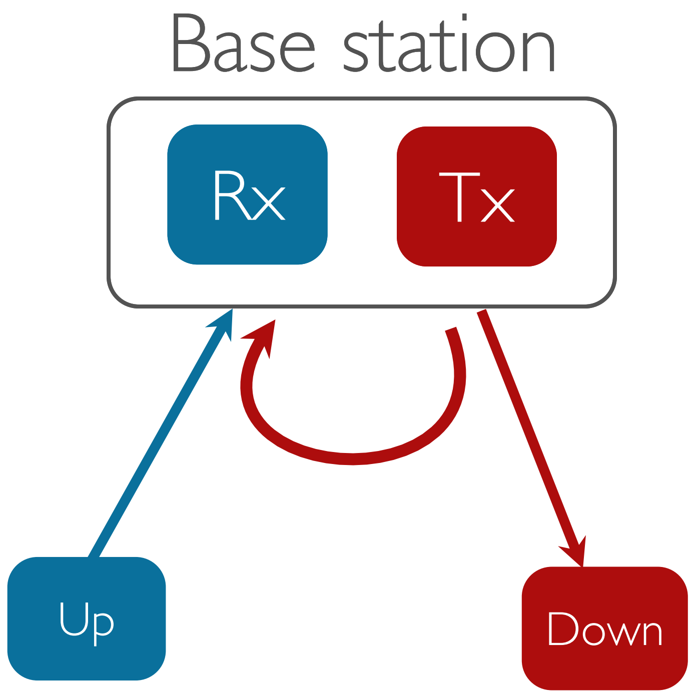
Full-duplex Spatial Multiplexing

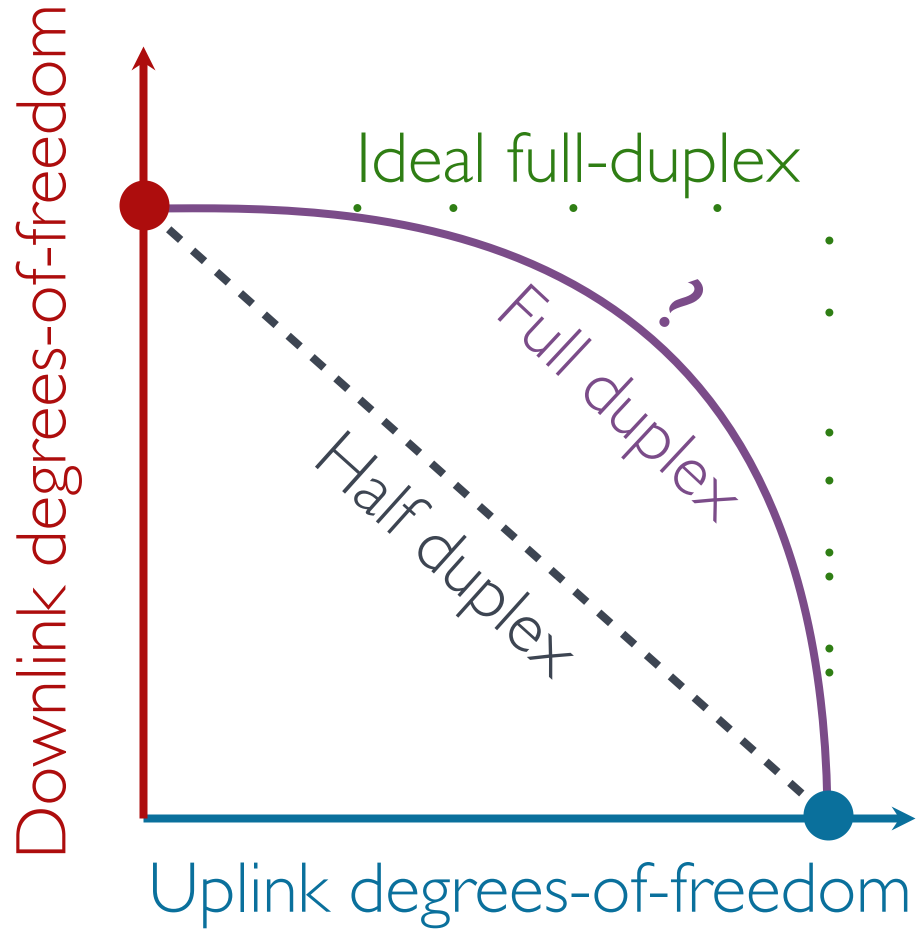


How do we balance beamformed suppression and spatial multiplexing?

Signal-scale Analysis of DoF

Rate Region for Wireless Full-duplex



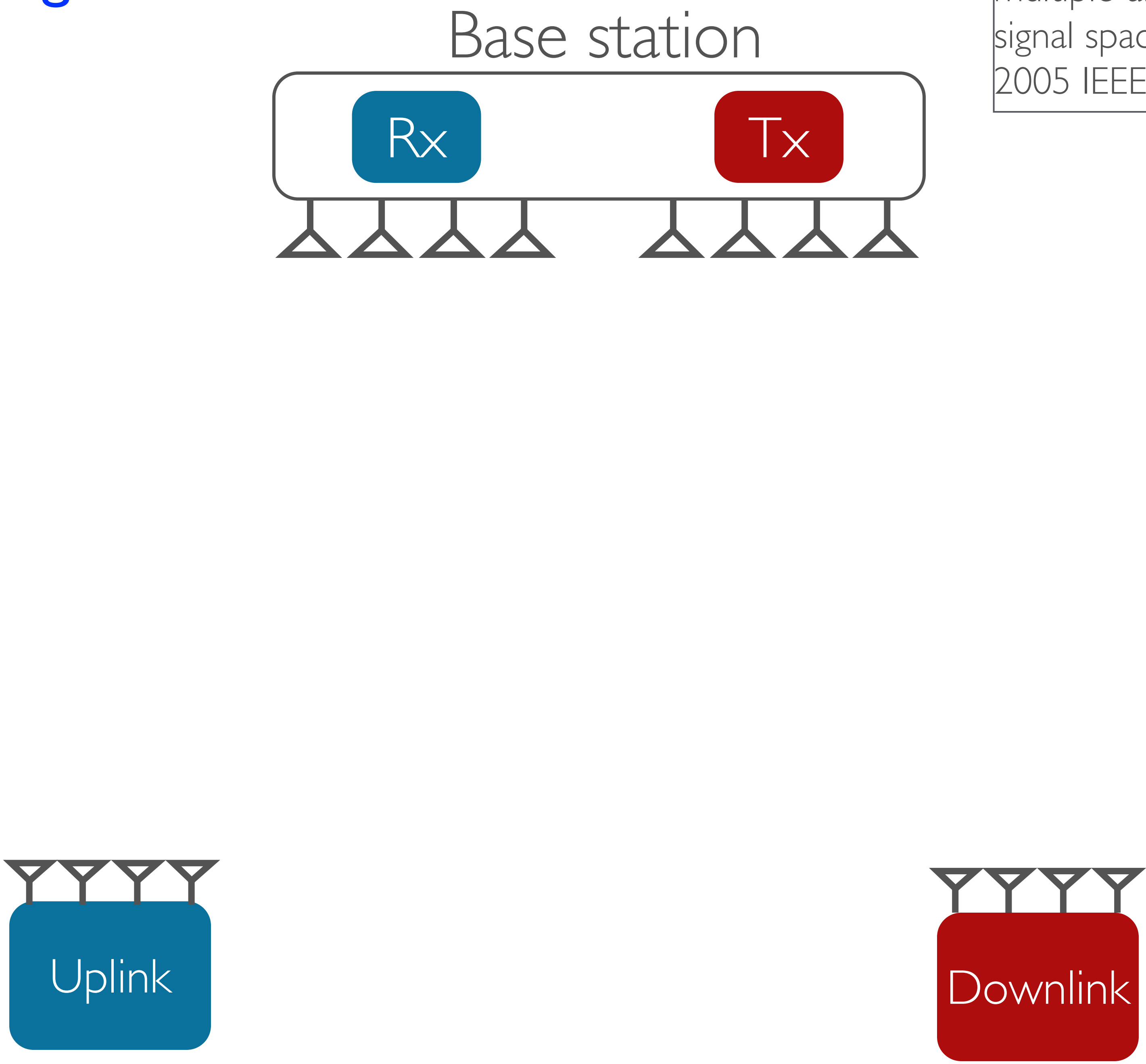


Choosing the Model

- Need tractable model, captures the physics
- Two key aspects to model
  - Antenna design
  - Scattering

Modeling Antennas

Poon, Broderson, and Tse. "Degrees of freedom in multiple-antenna channels: a signal space approach." 2005 IEEE Trans Info Thry.



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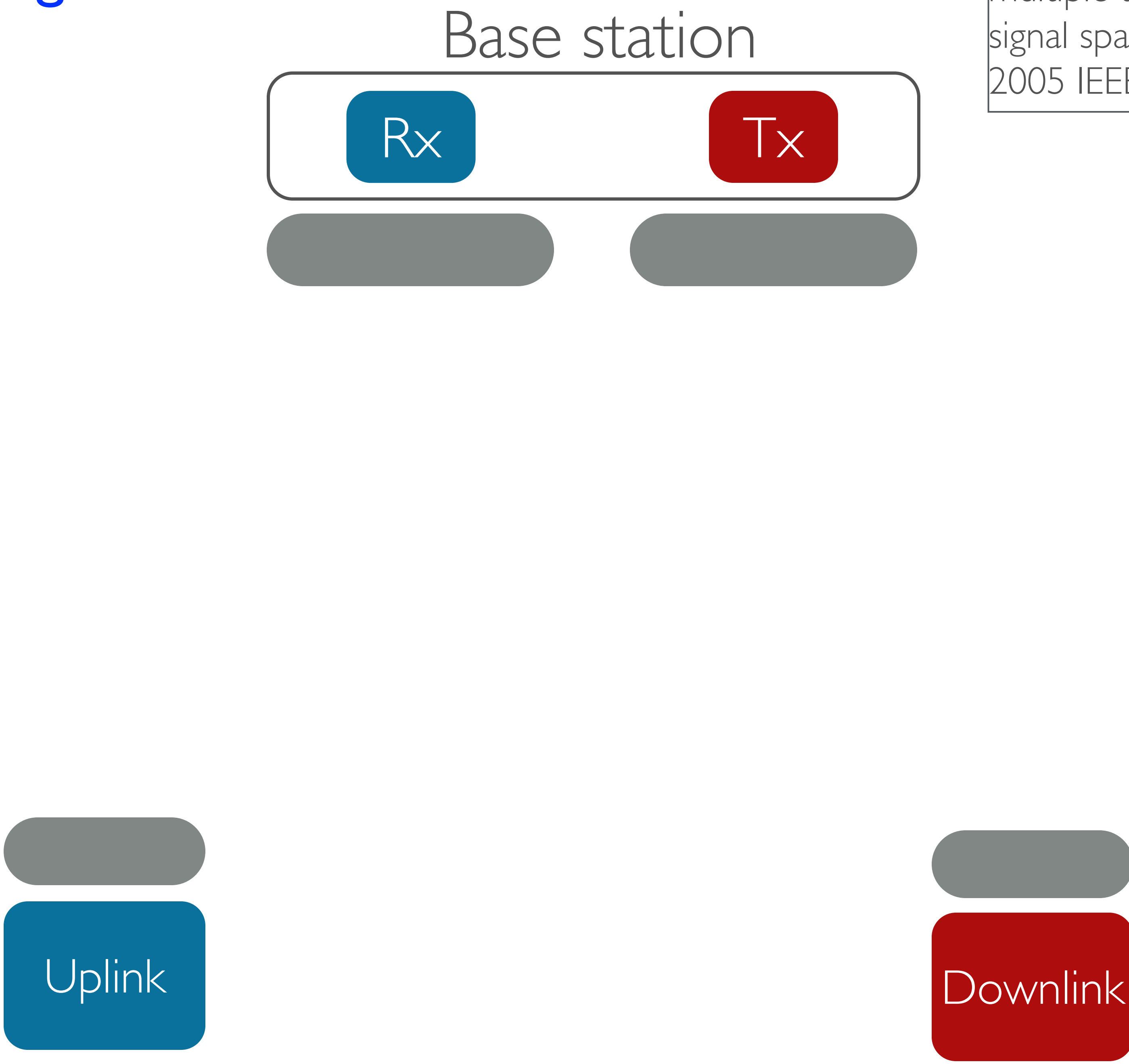

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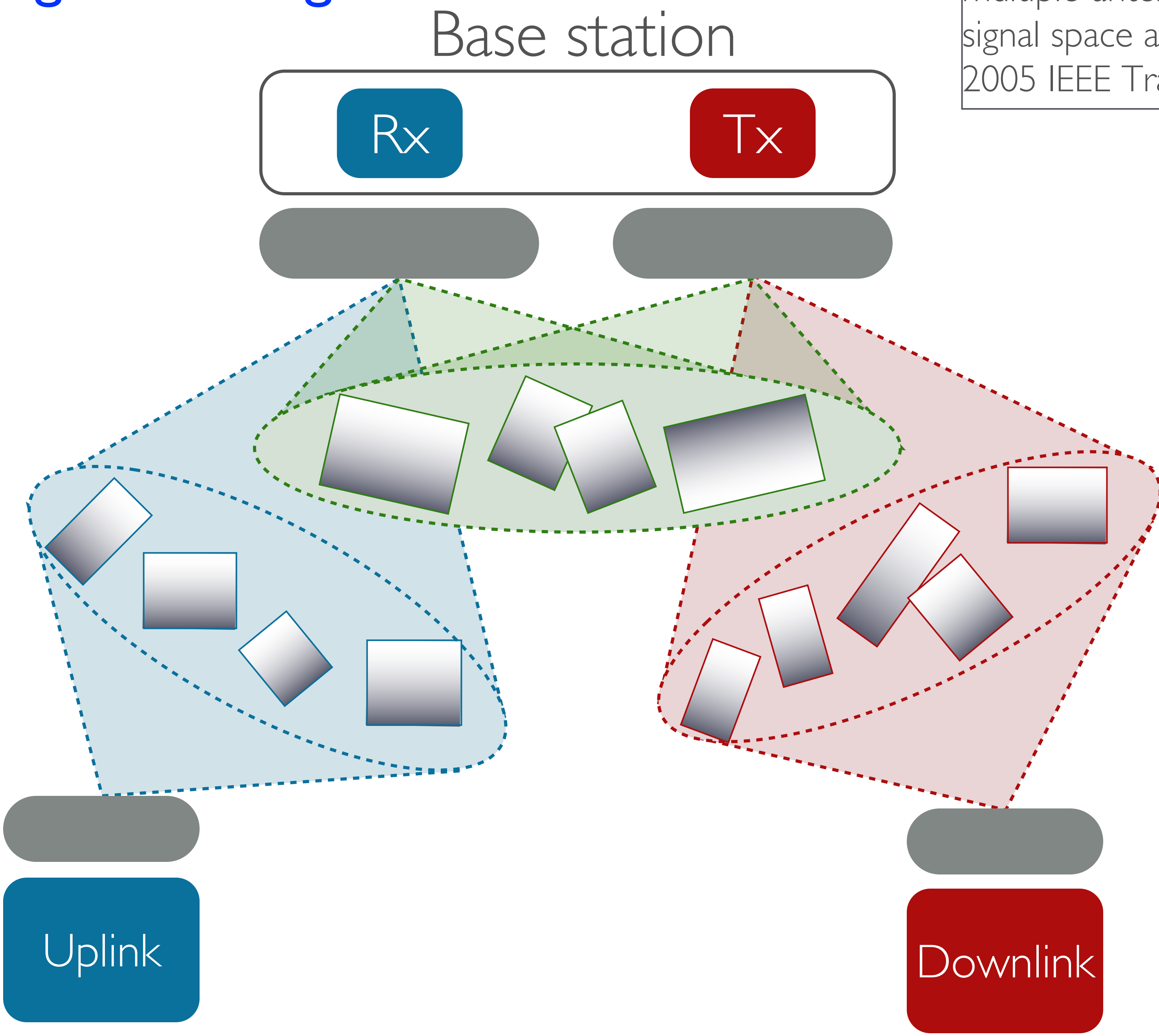

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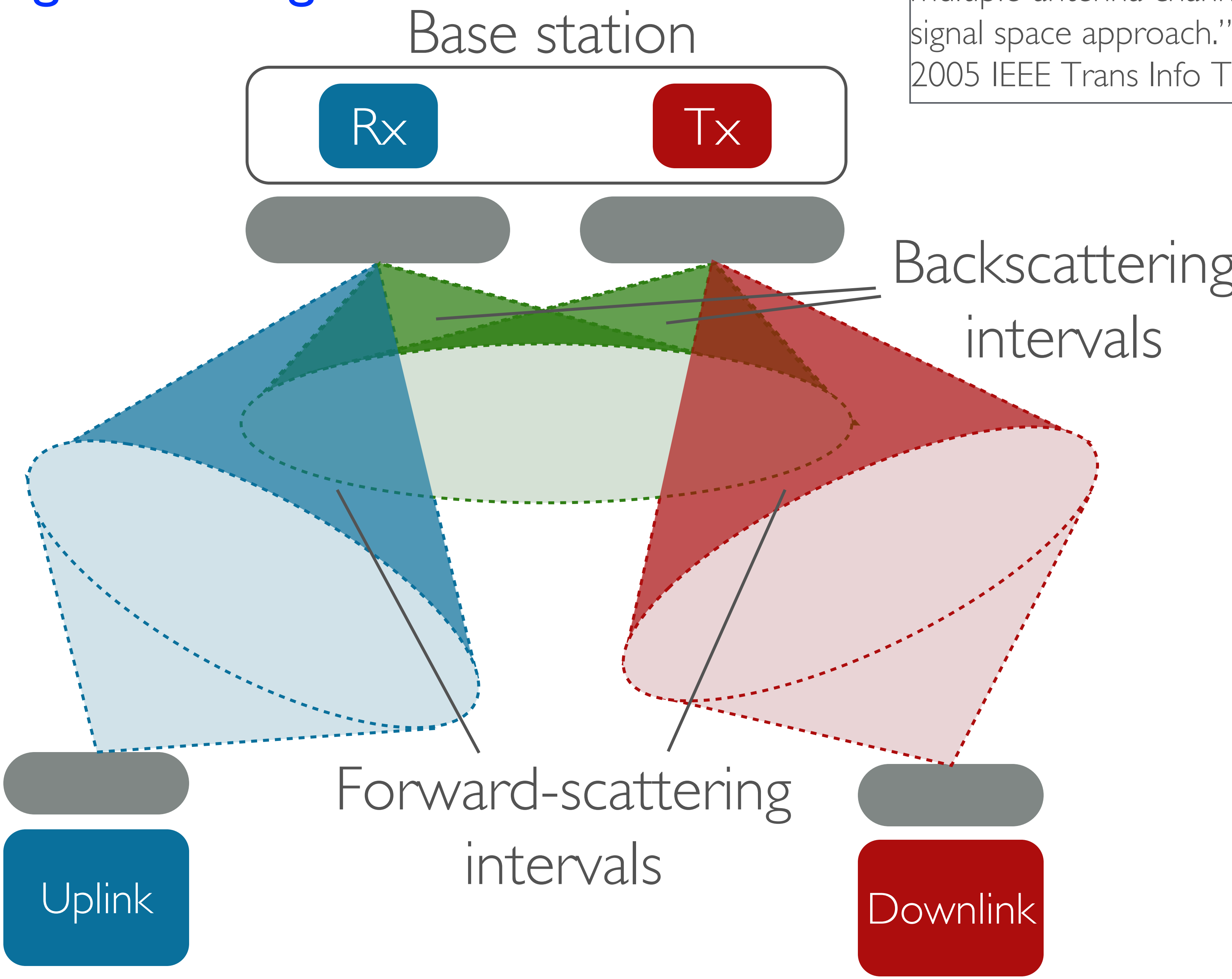
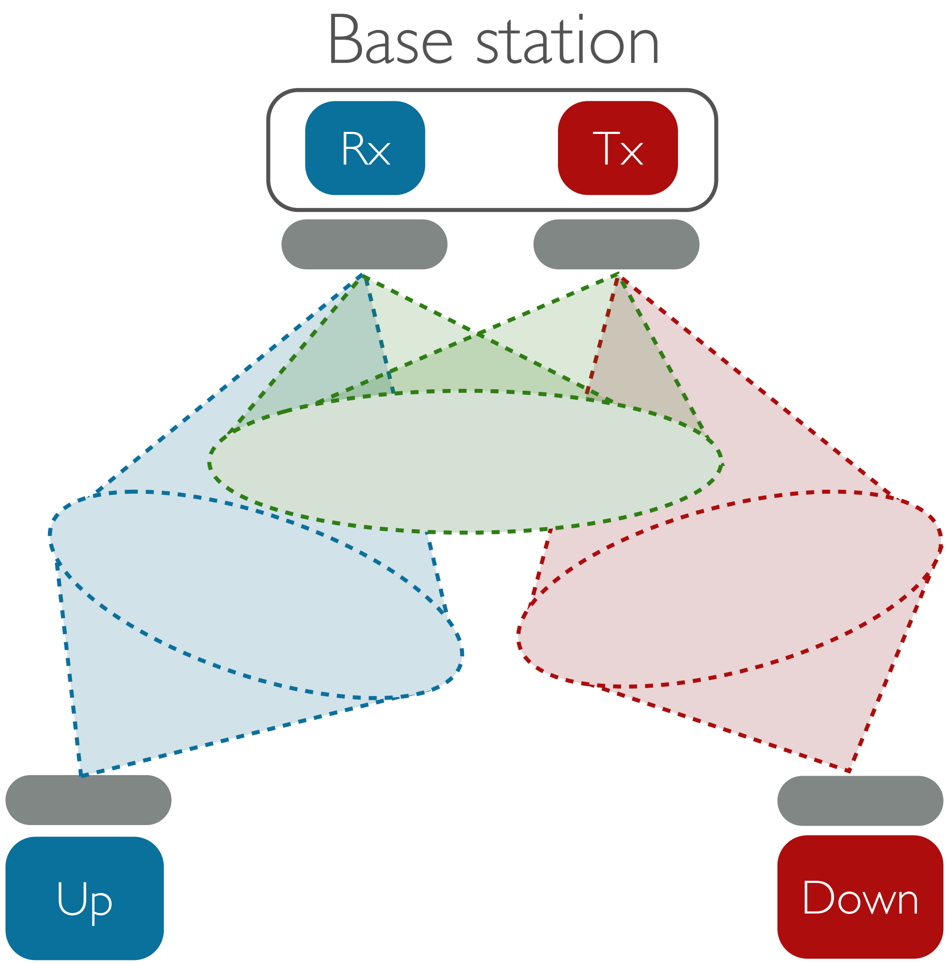
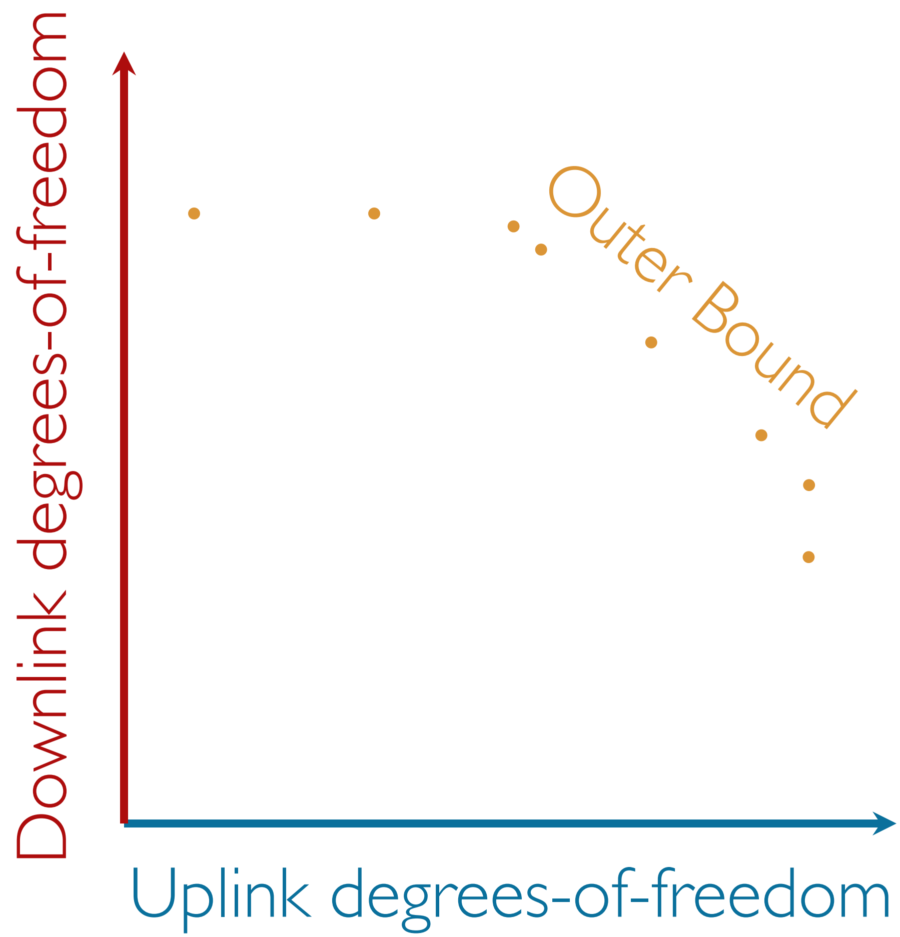


Solving the Degrees-of-freedom Tradeoff

Everett and Sabharwal, "Spatial Self-interference Isolation for In-band Full-duplex Wireless…,"





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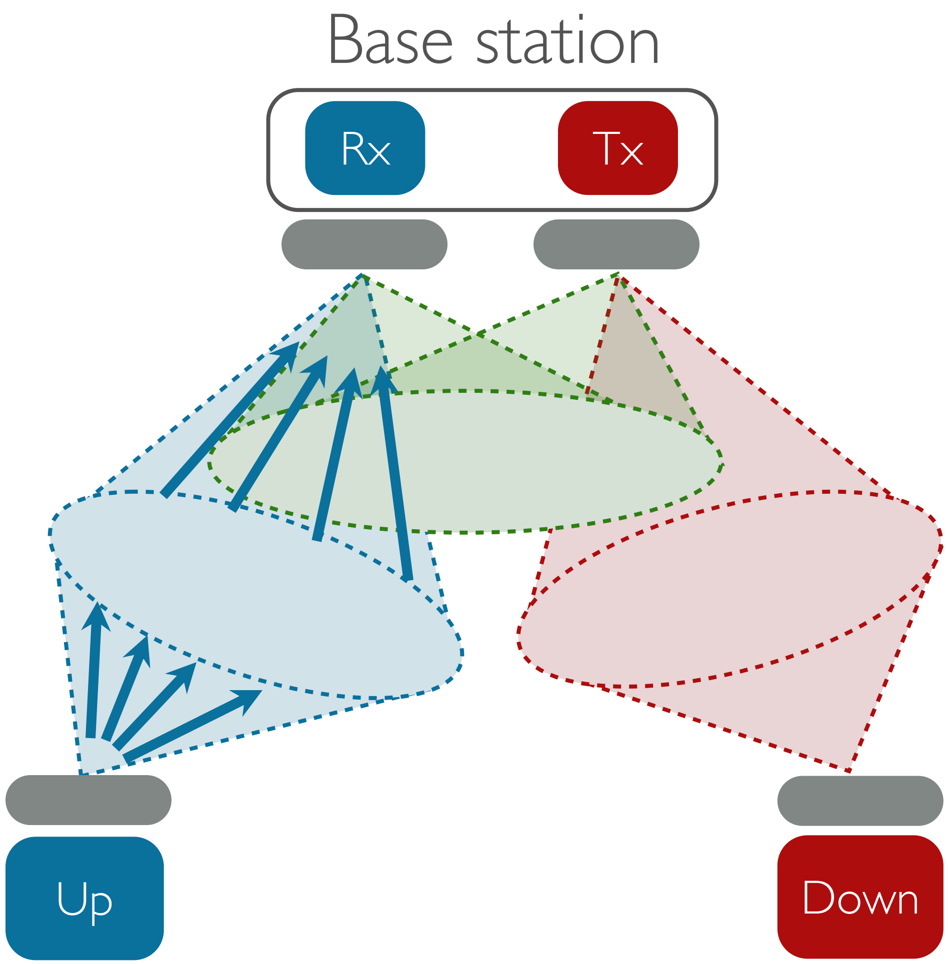

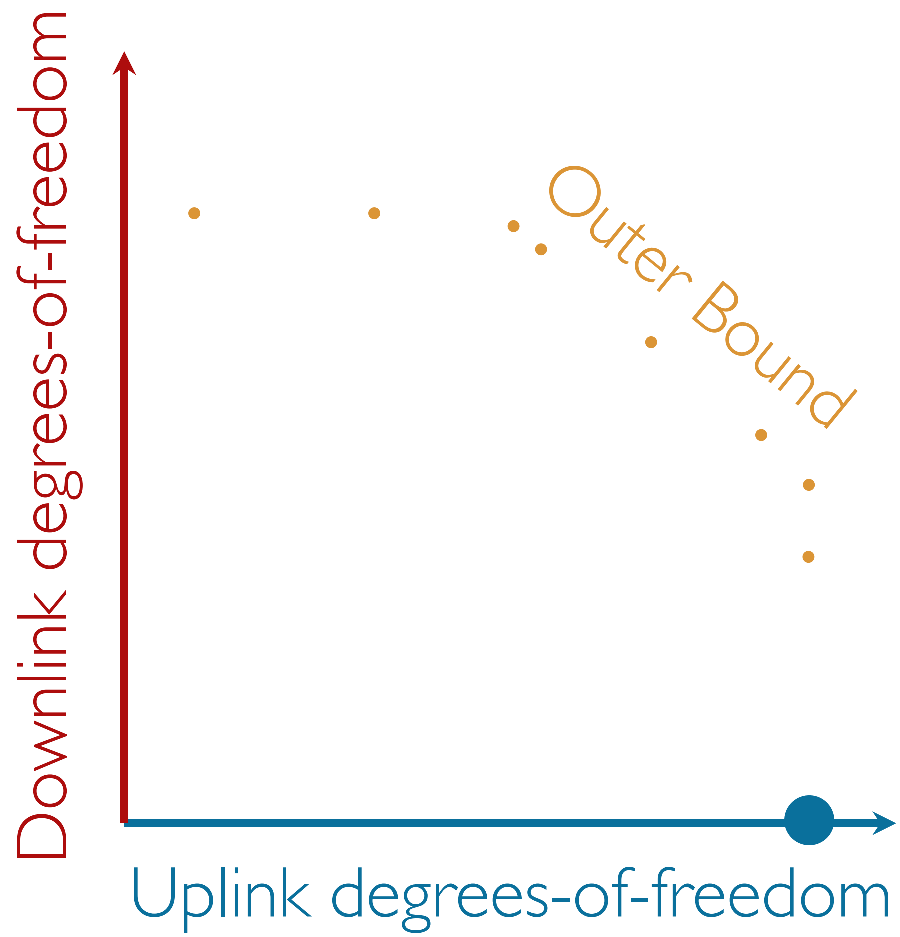

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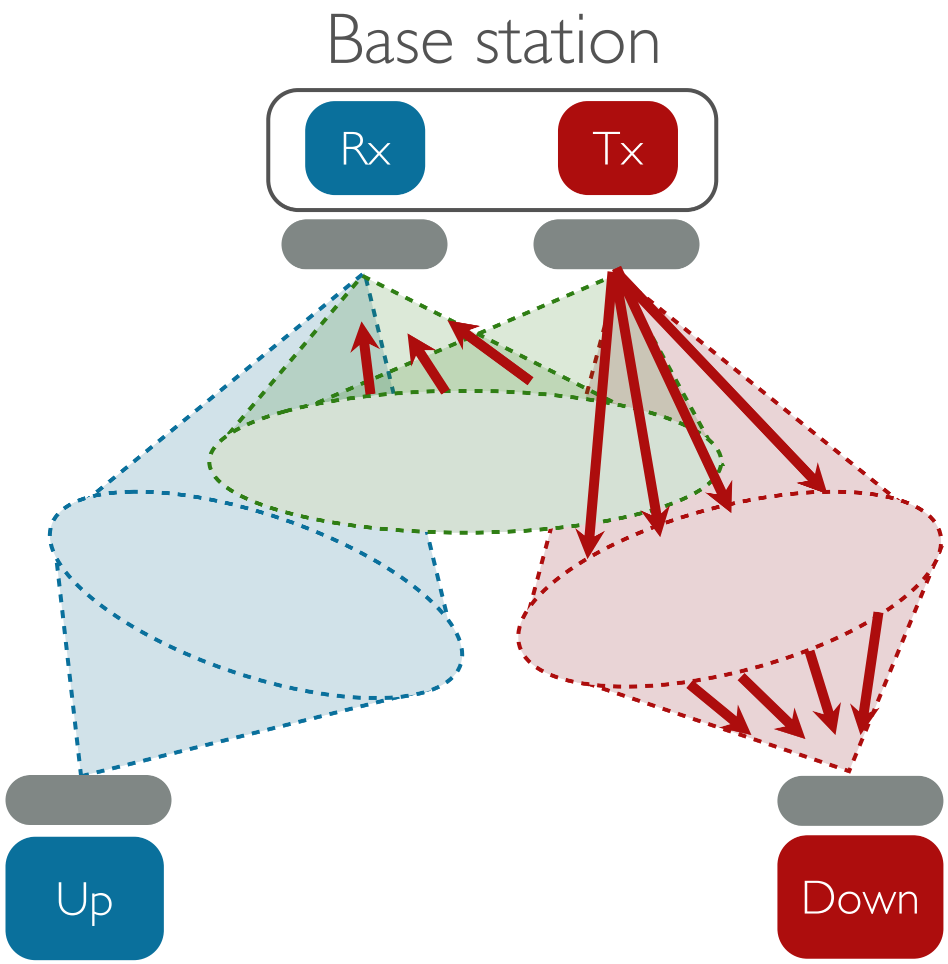

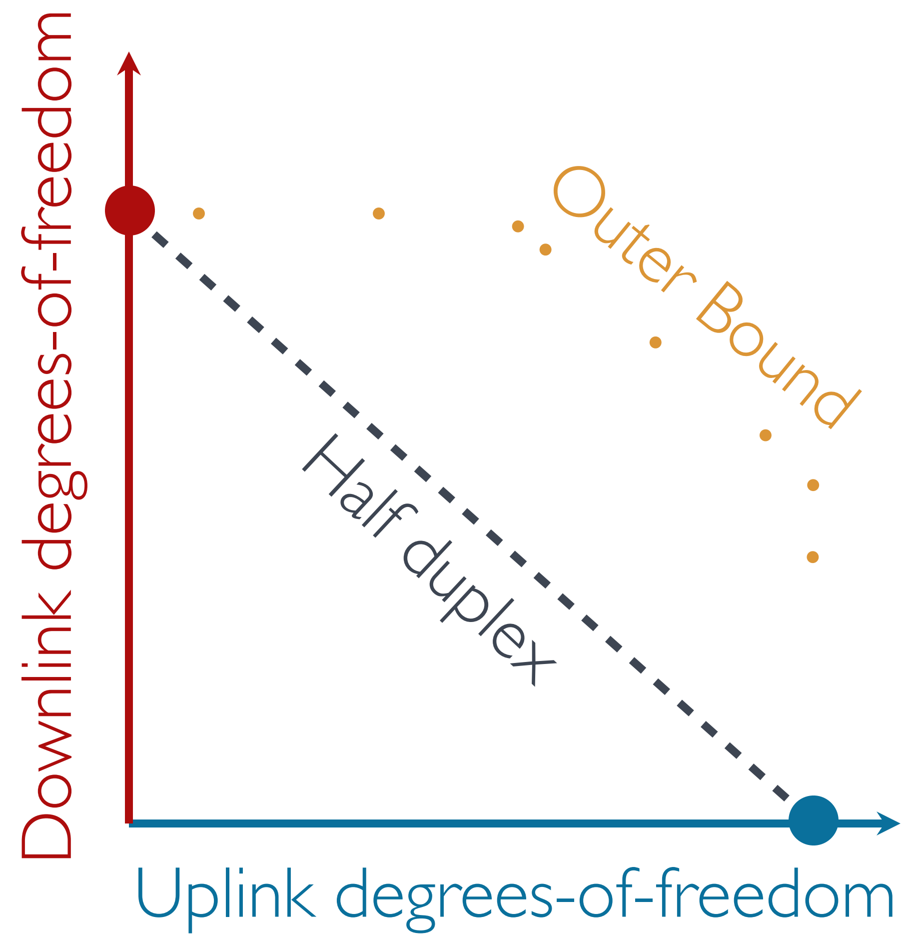

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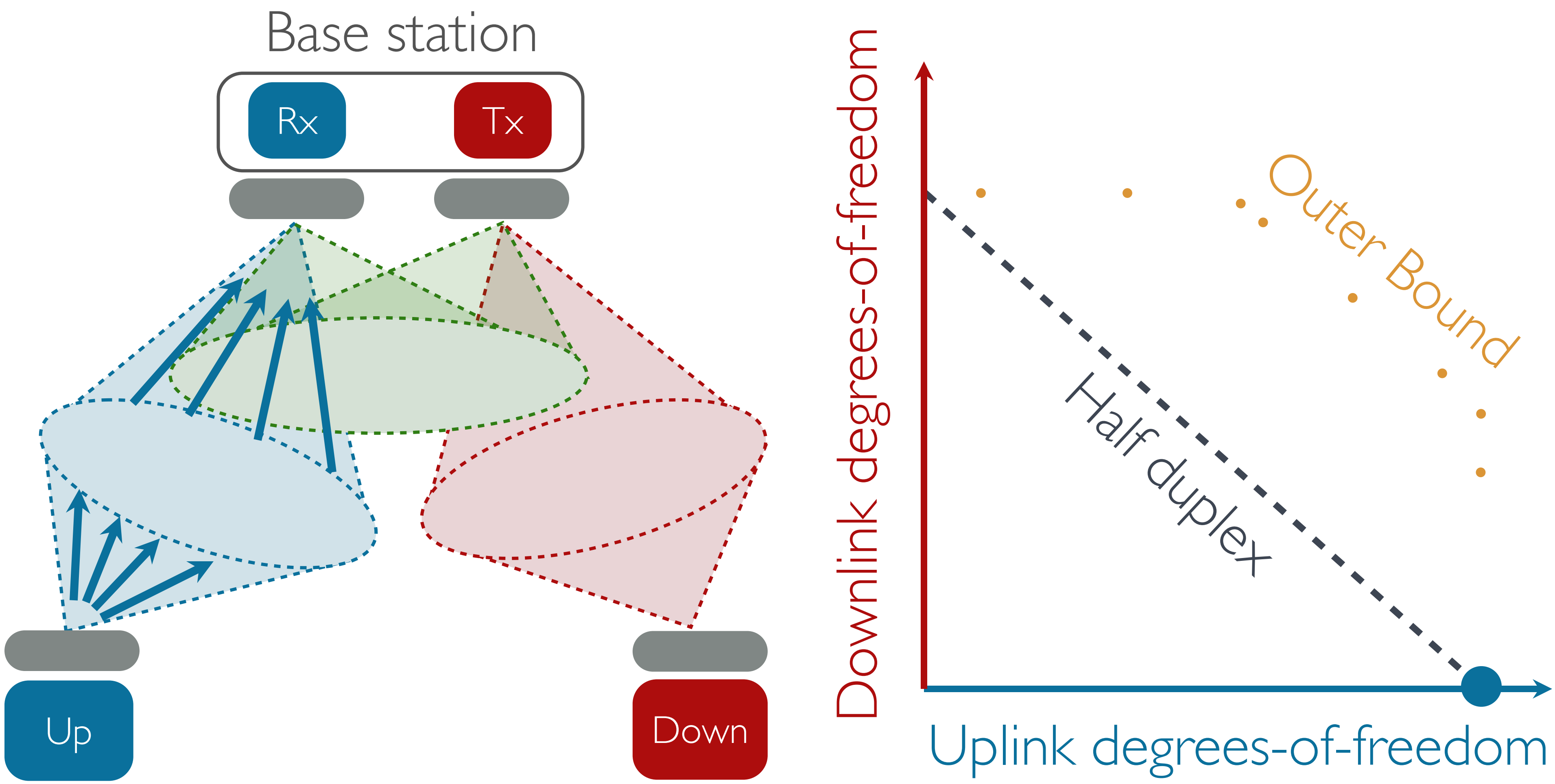

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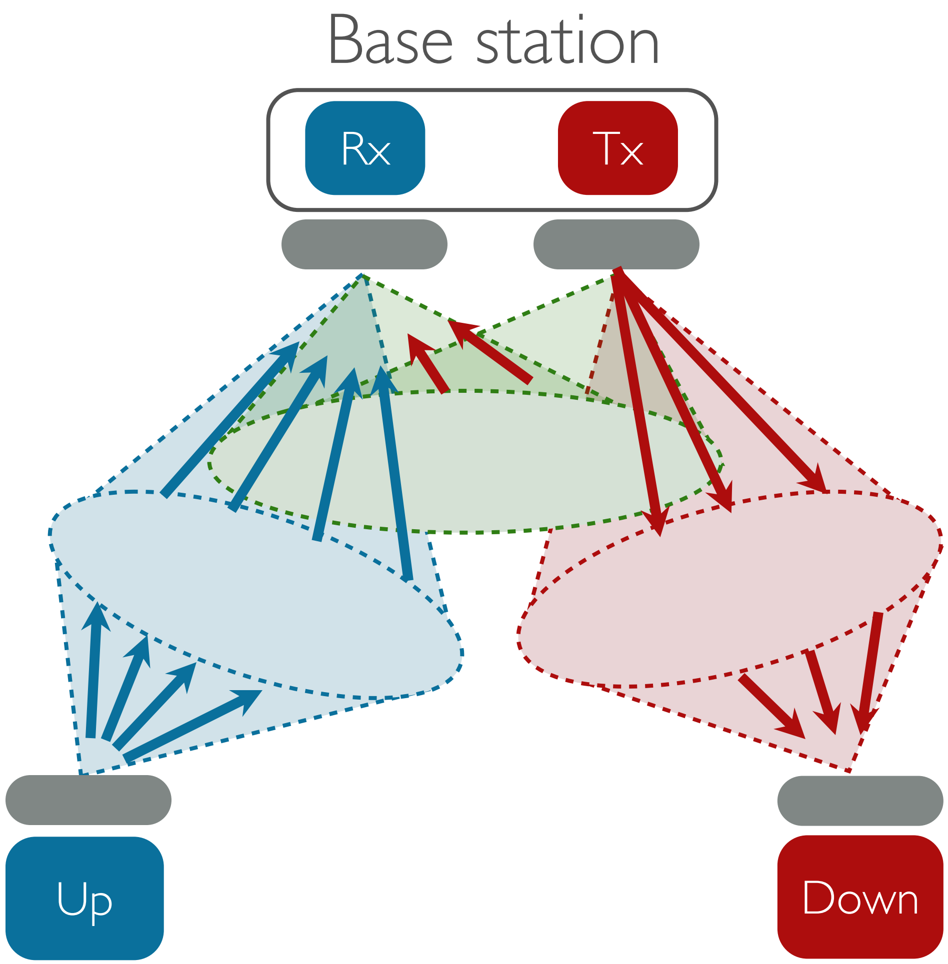

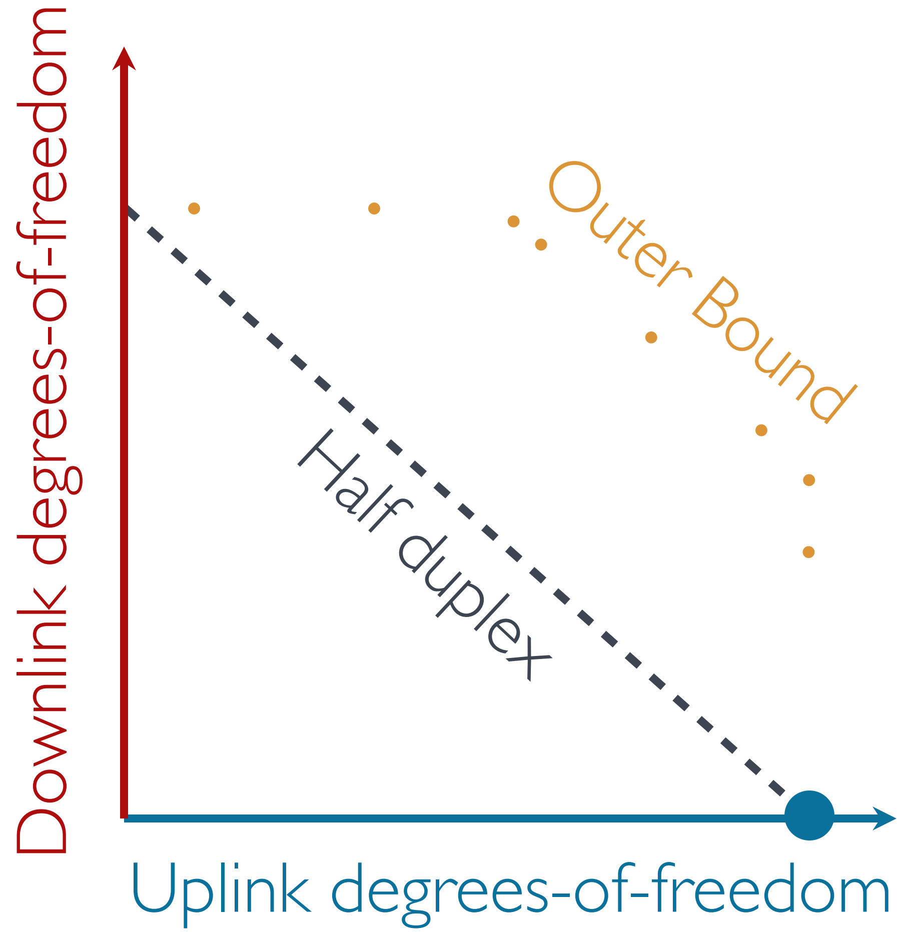

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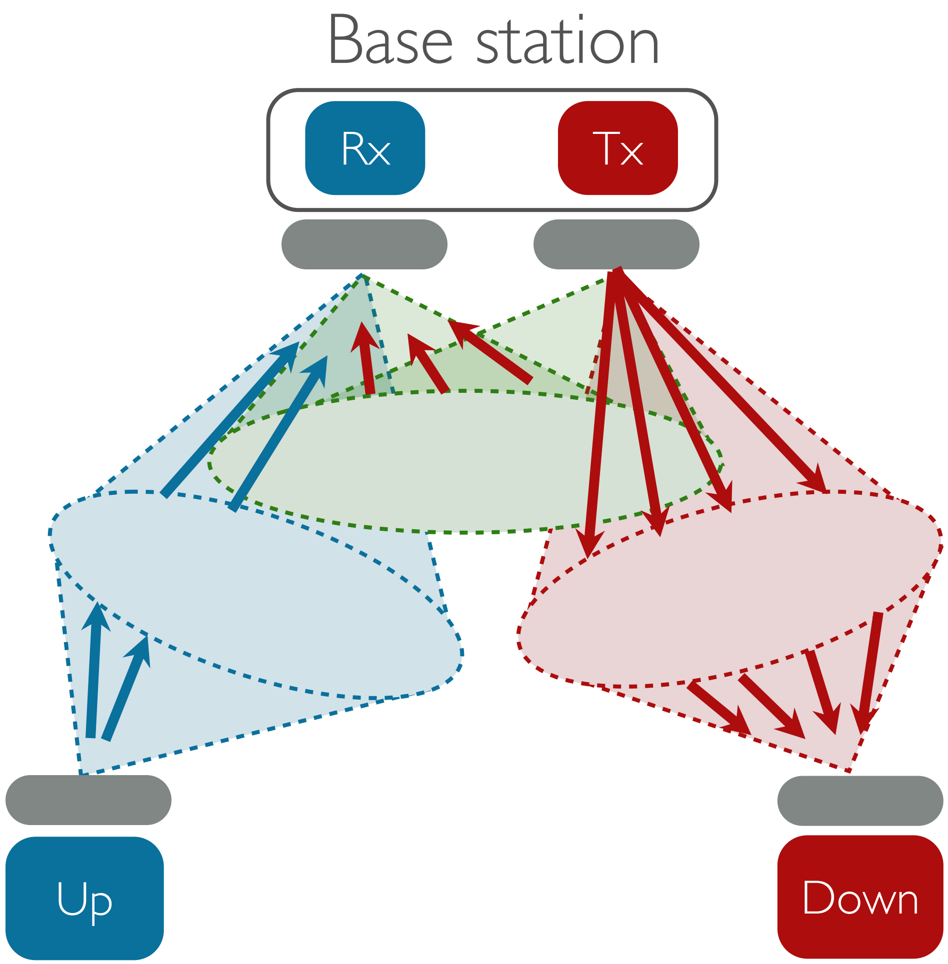
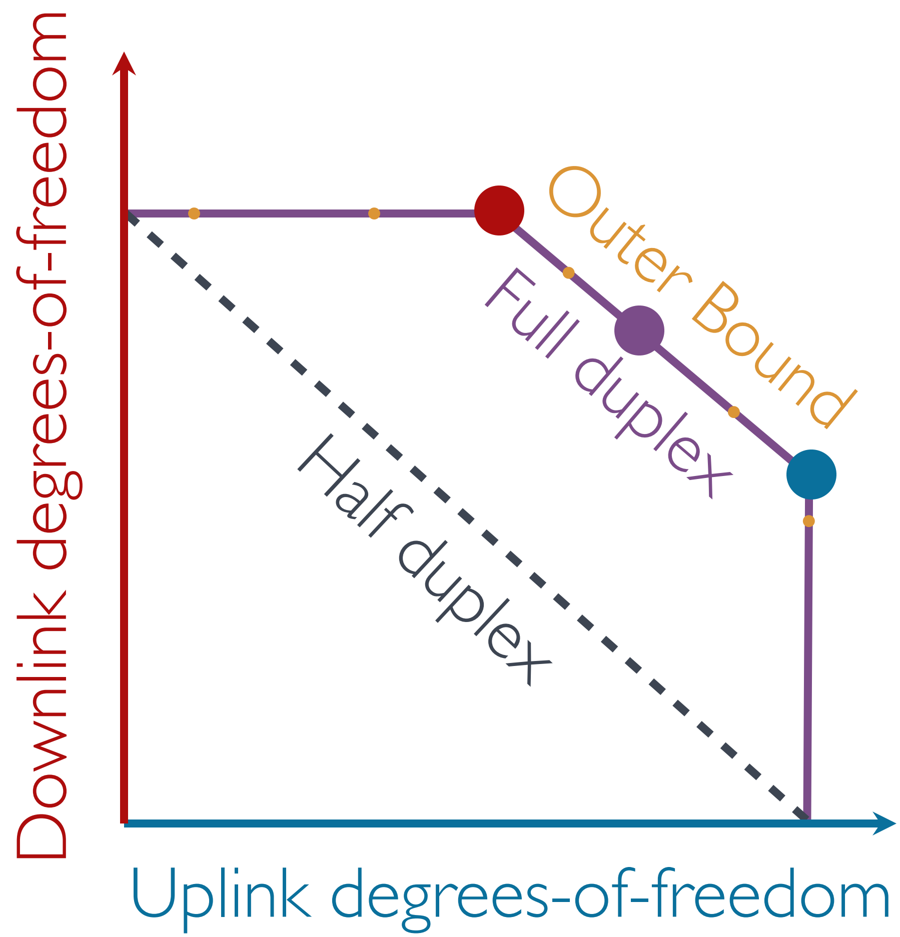
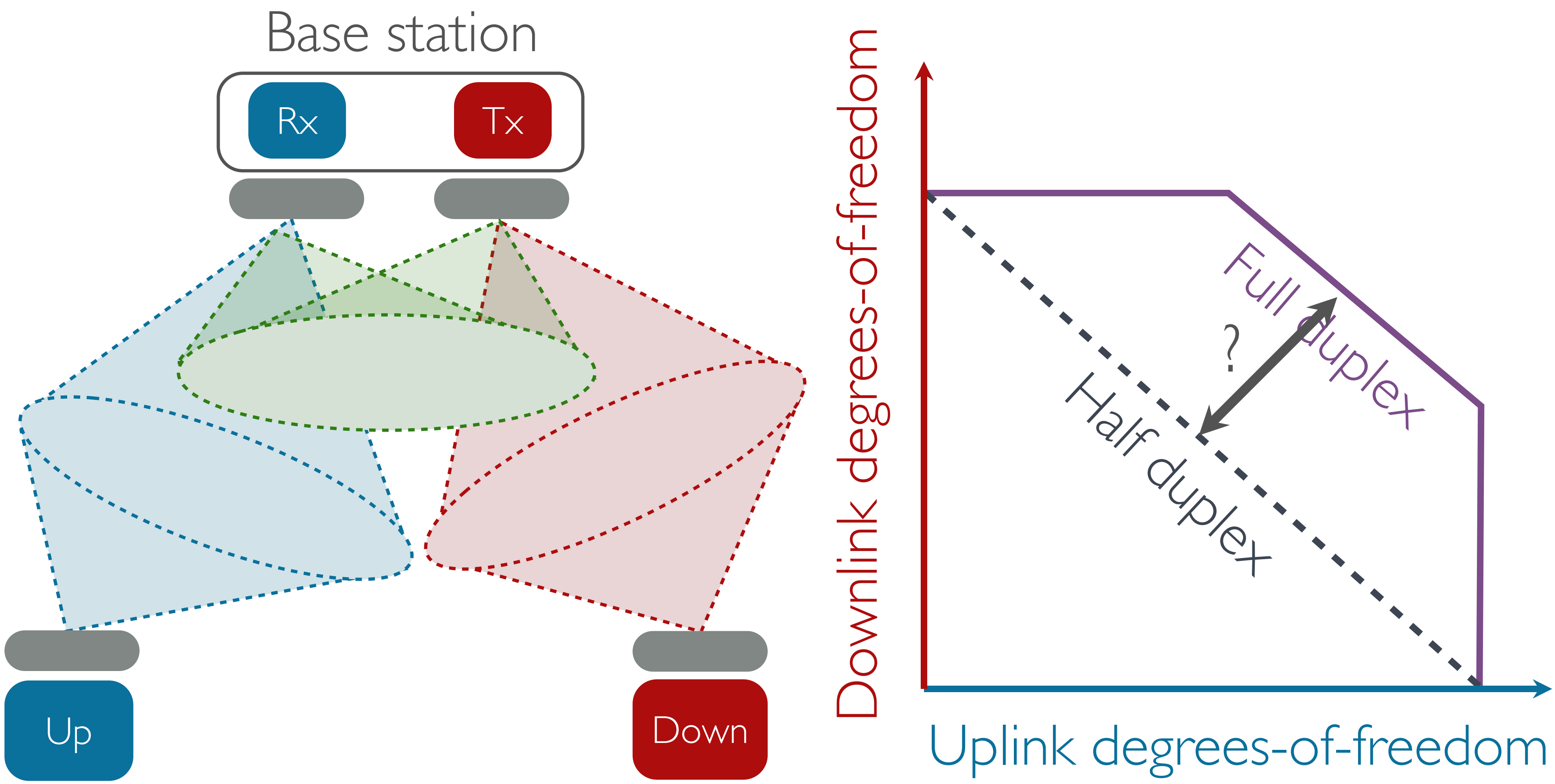
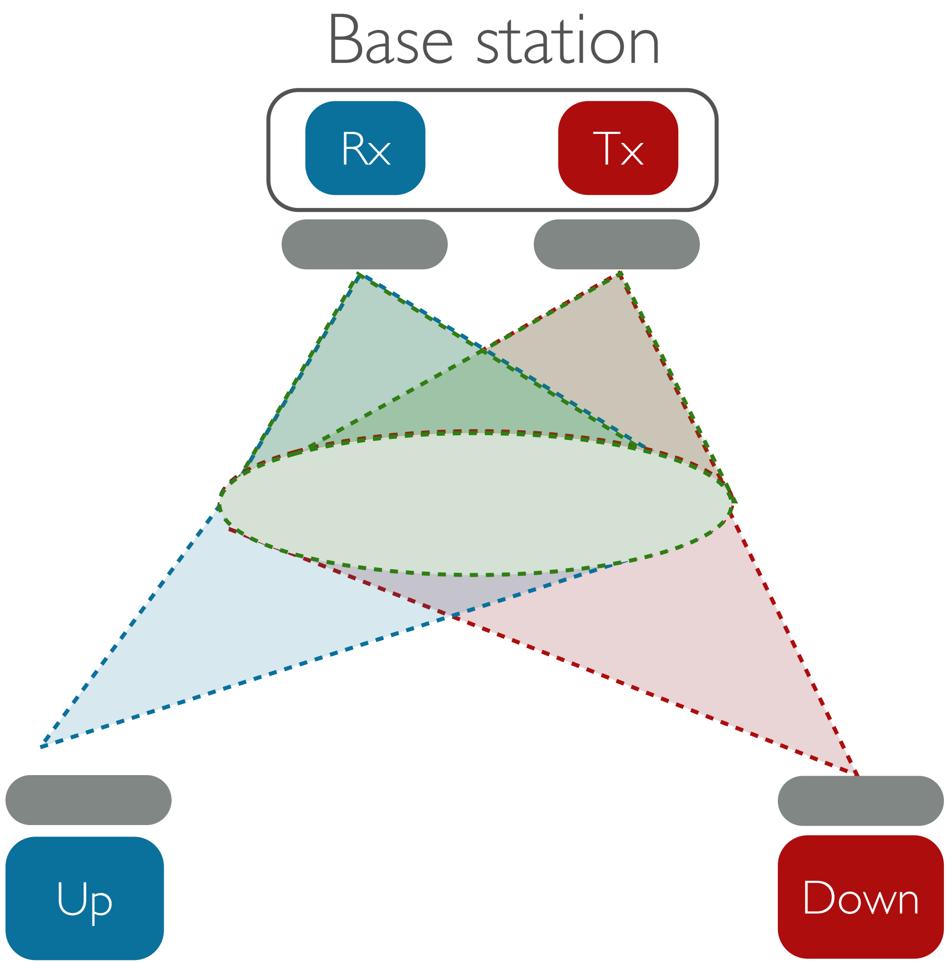


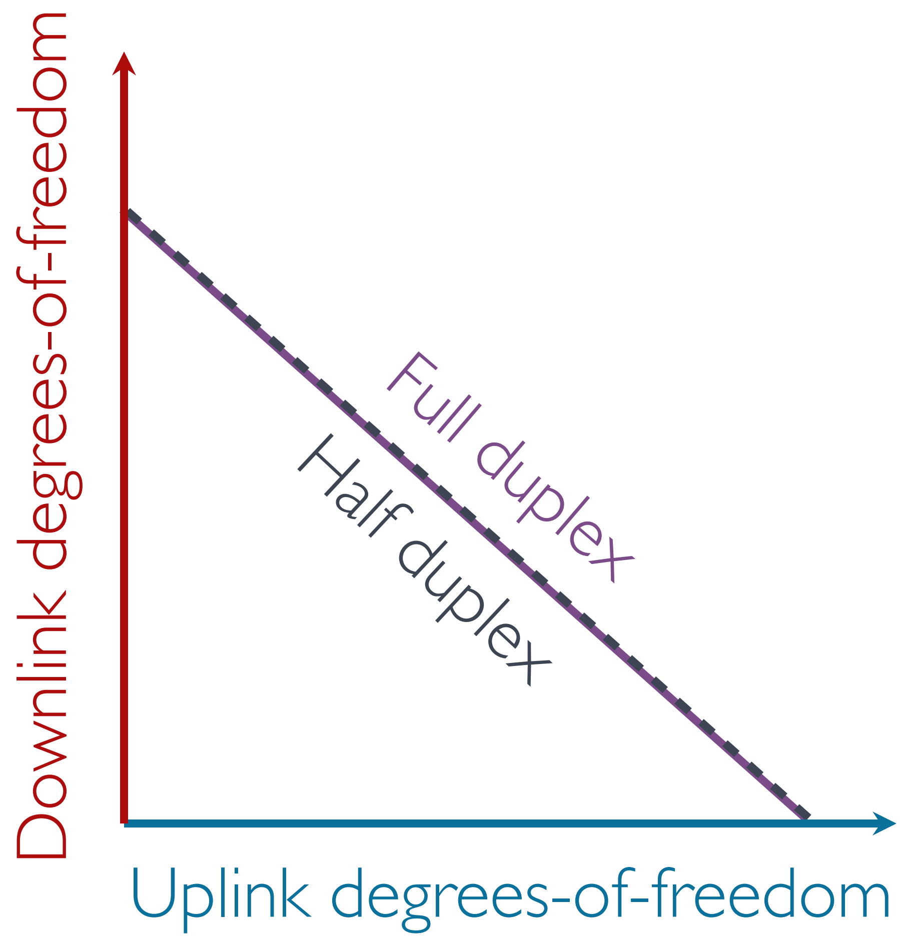


When, and By How Much, Is Full-duplex Better?

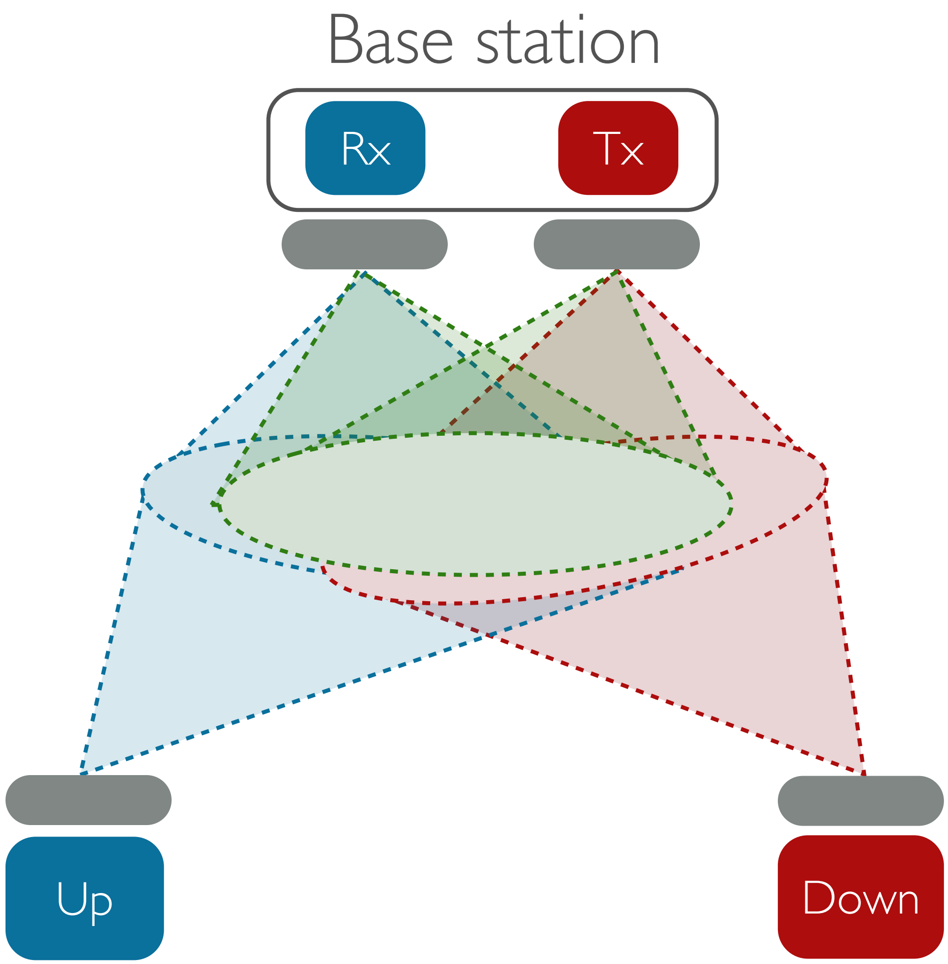


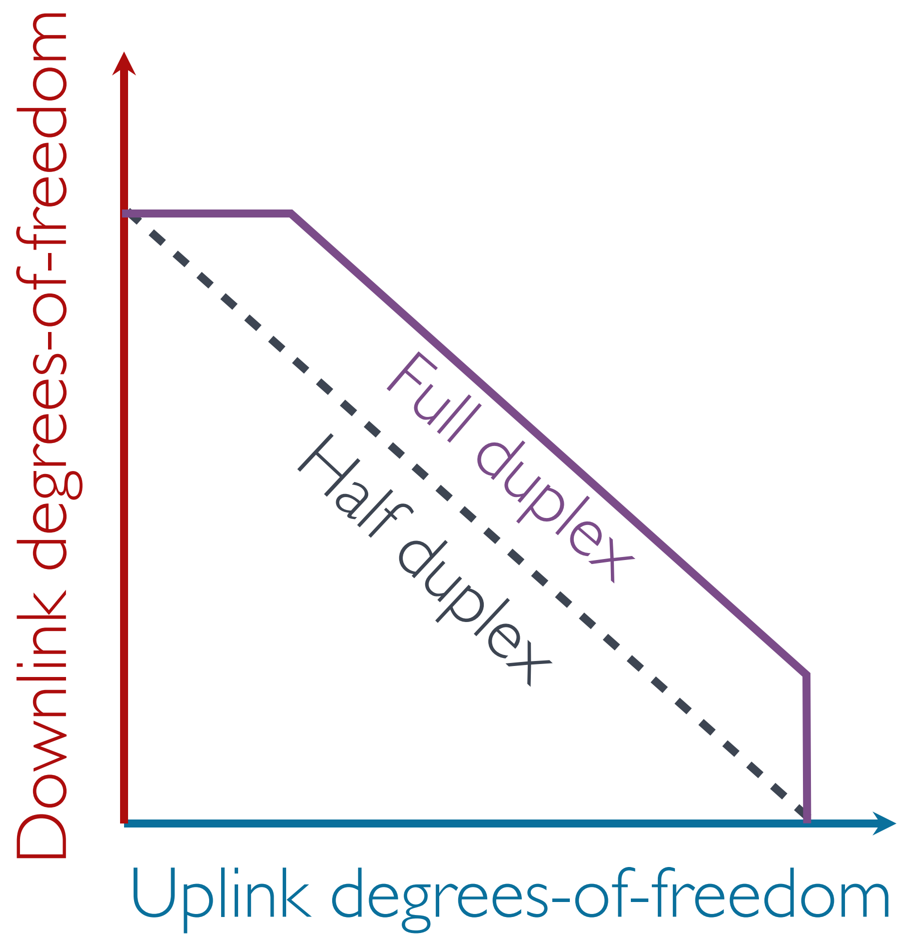
If scattering overlapped, and base station arrays no larger than mobile arrays, <u>no gain</u>





Gain proportional to non-overlap between backscattering forward scattering





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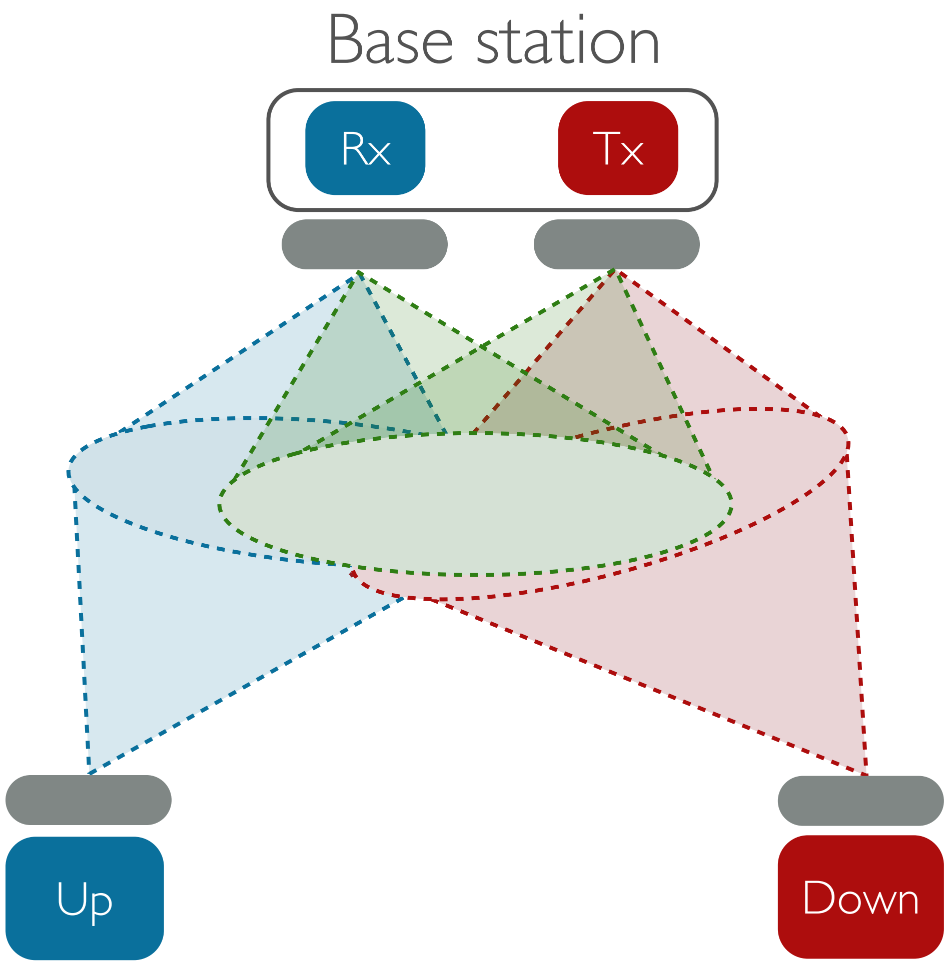
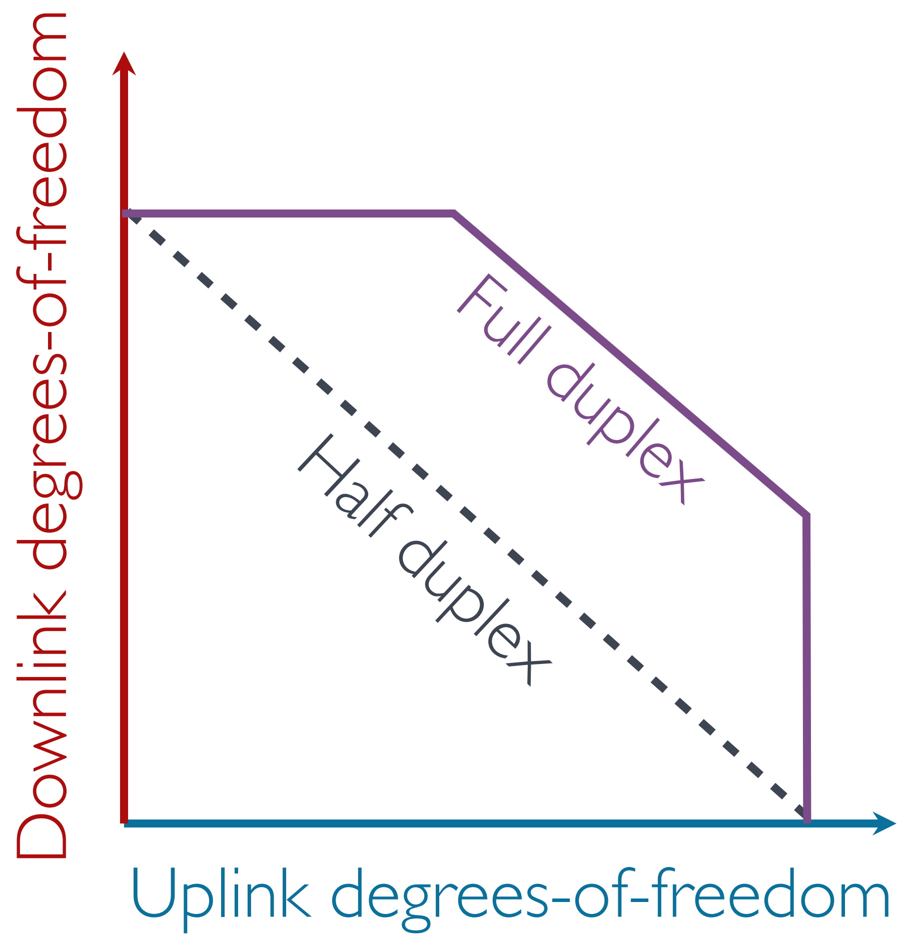
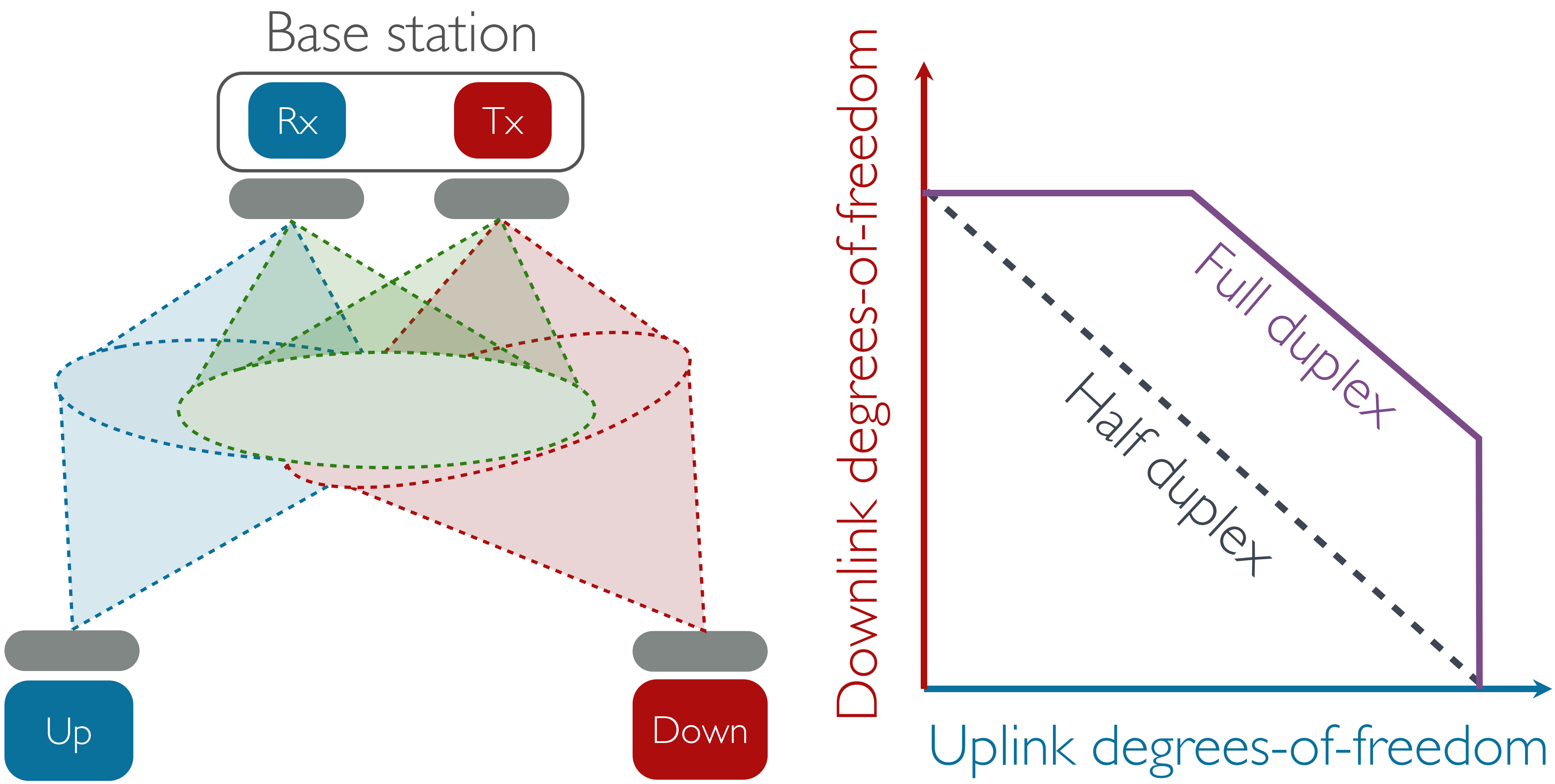


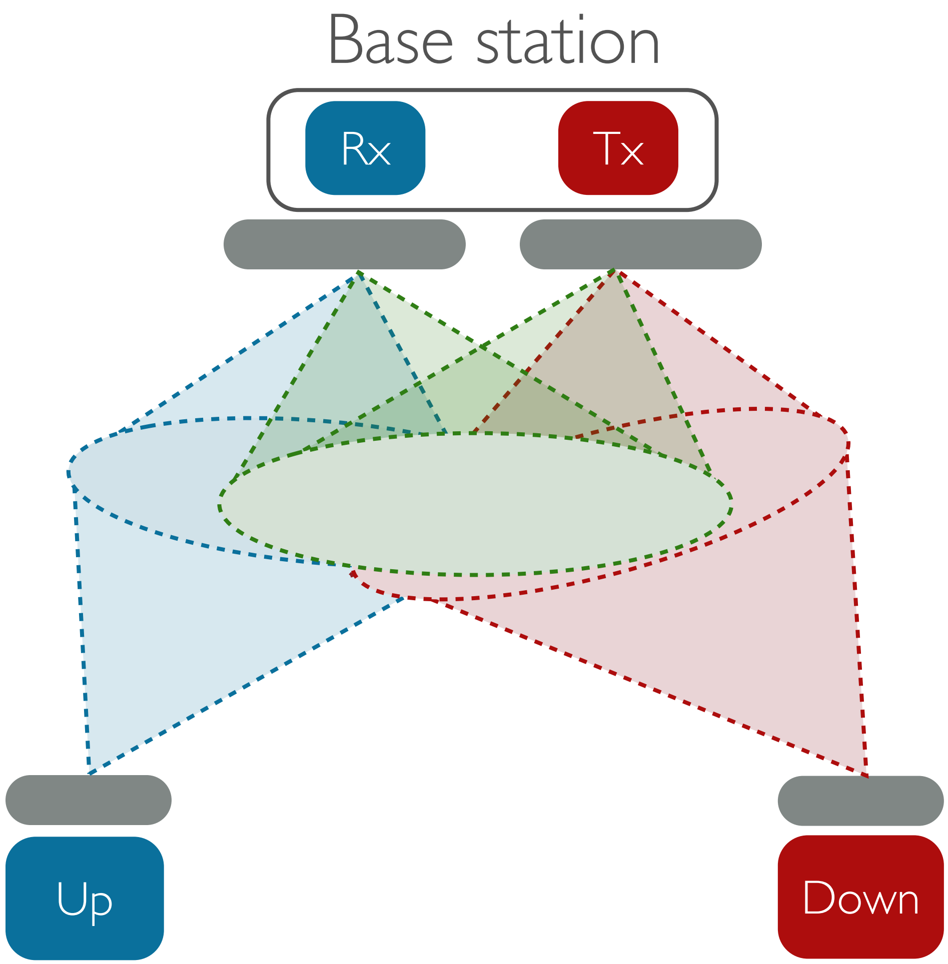


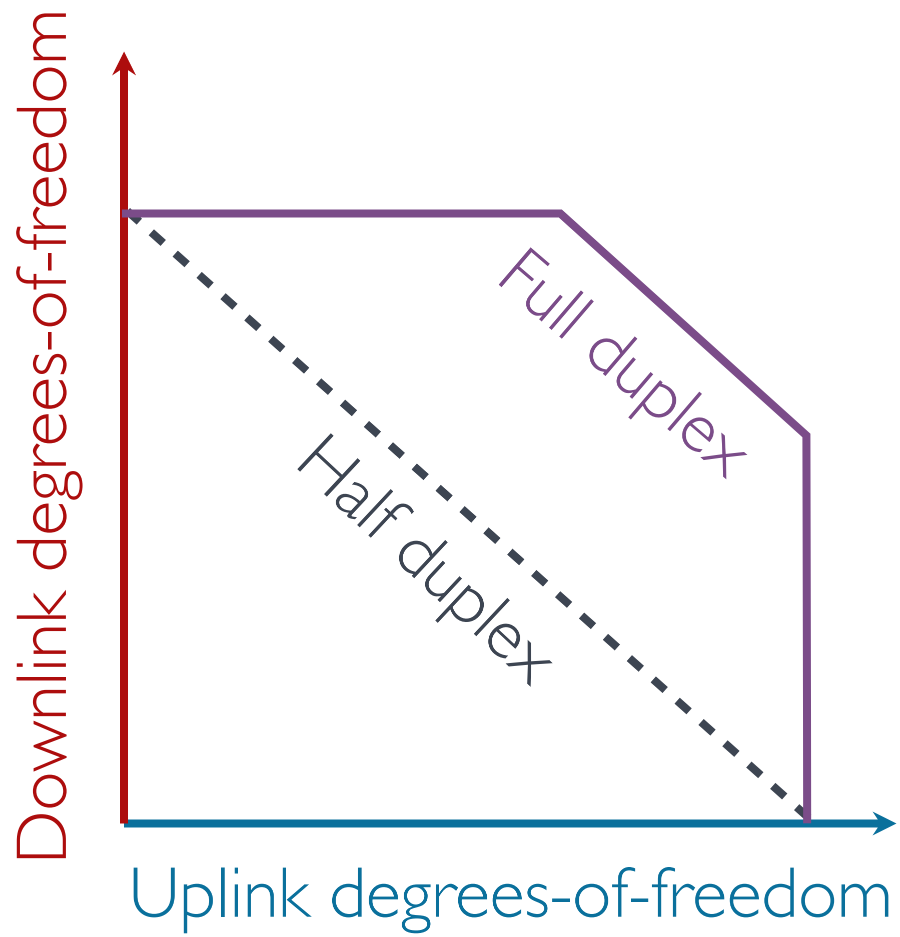
Further improve full-duplex with <u>larger</u> arrays at base station



Leverage extra DoFs for nulling

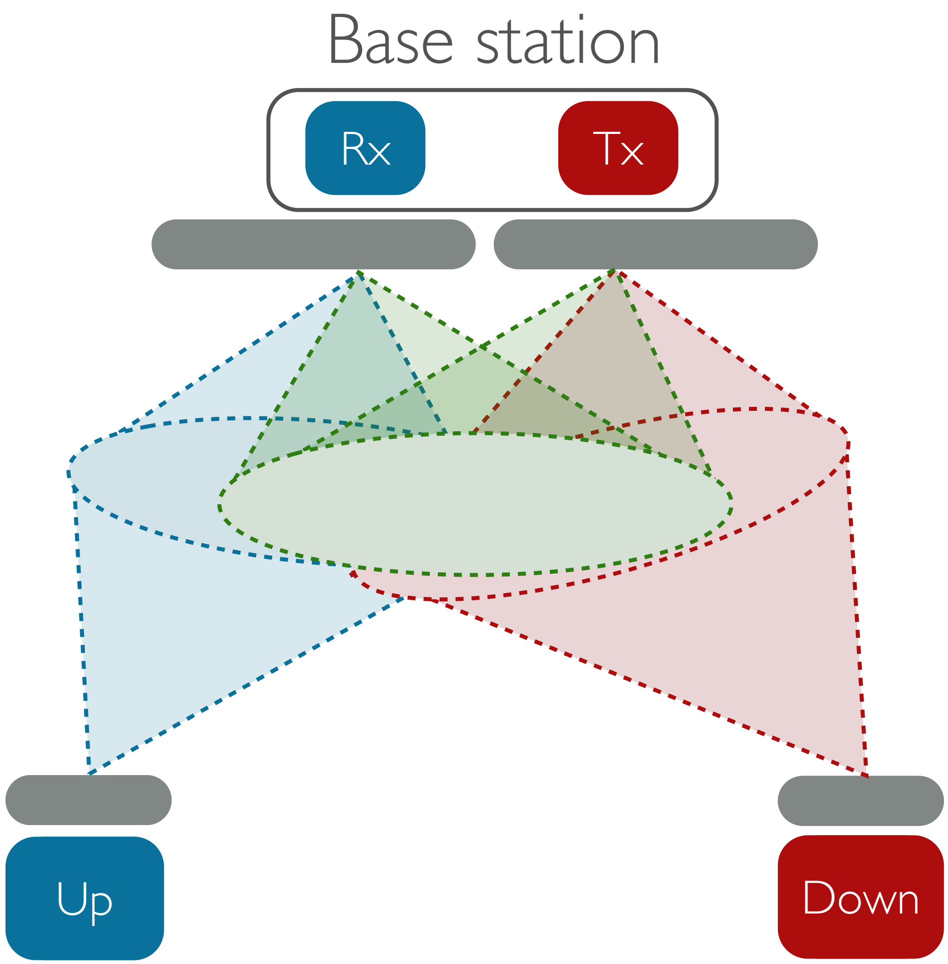
Further improve full-duplex with <u>larger</u> arrays at base station

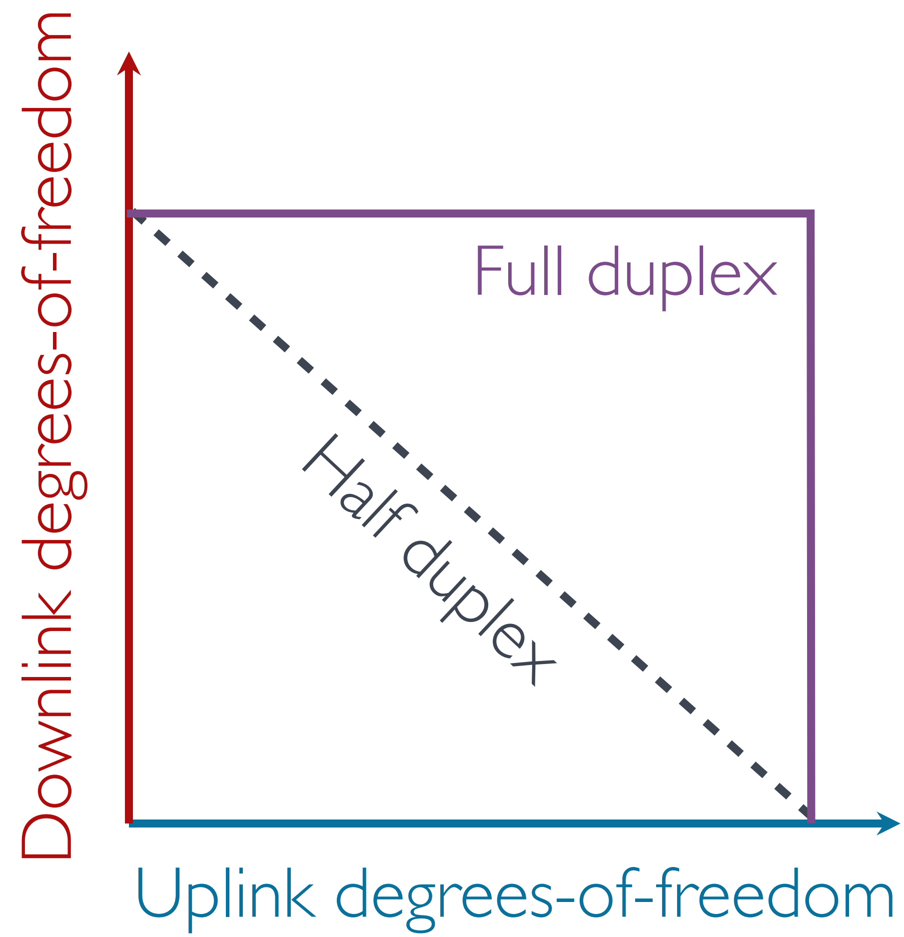




Leverage extra DoFs for nulling

Further improve full-duplex with larger arrays at base station ("Massive MIMO Regime")

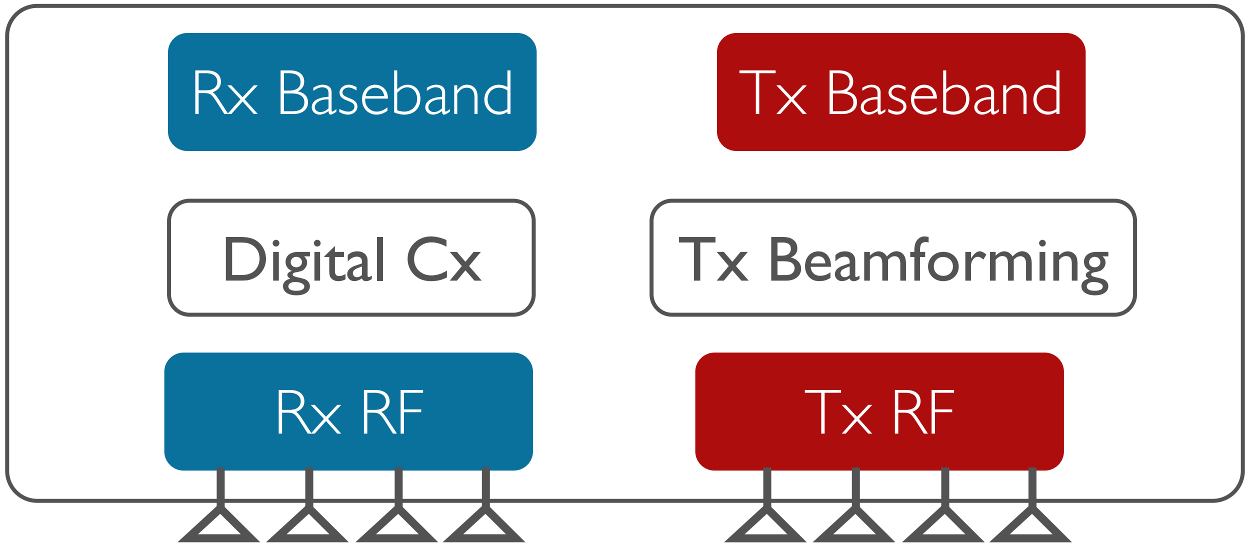




Spatial degrees-of-freedom in large-array full-duplex: the impact of backscattering

Evan Everett* and Ashutosh Sabharwal

Questions to Answer



1. In what conditions is all-digital FD feasible?

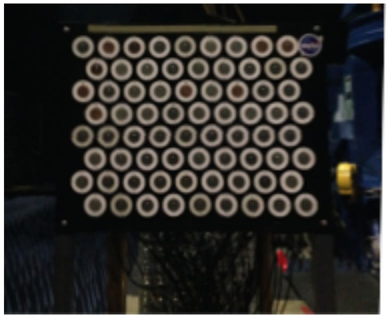
Answer with info-theoretic analysis

2. What are practical algorithms for all-digital FD?

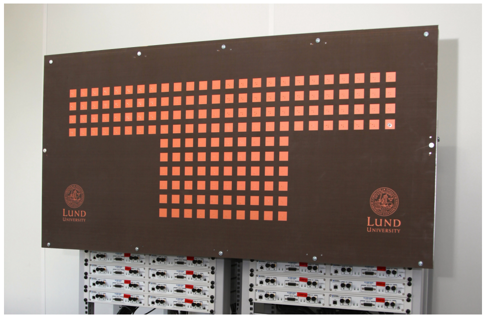
Answer with design and experiment

Suppression via Transmit Beamforming

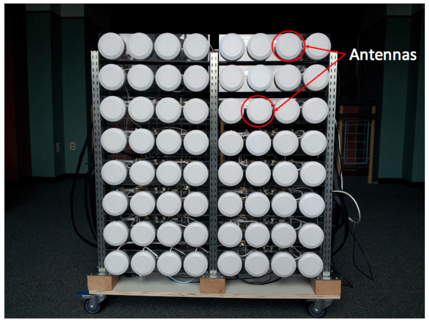
NASA array

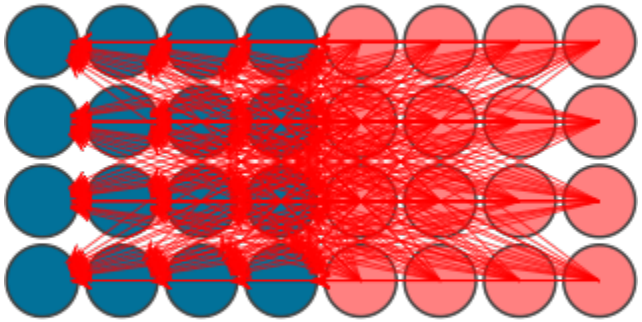


Lund array



Rice Argos array

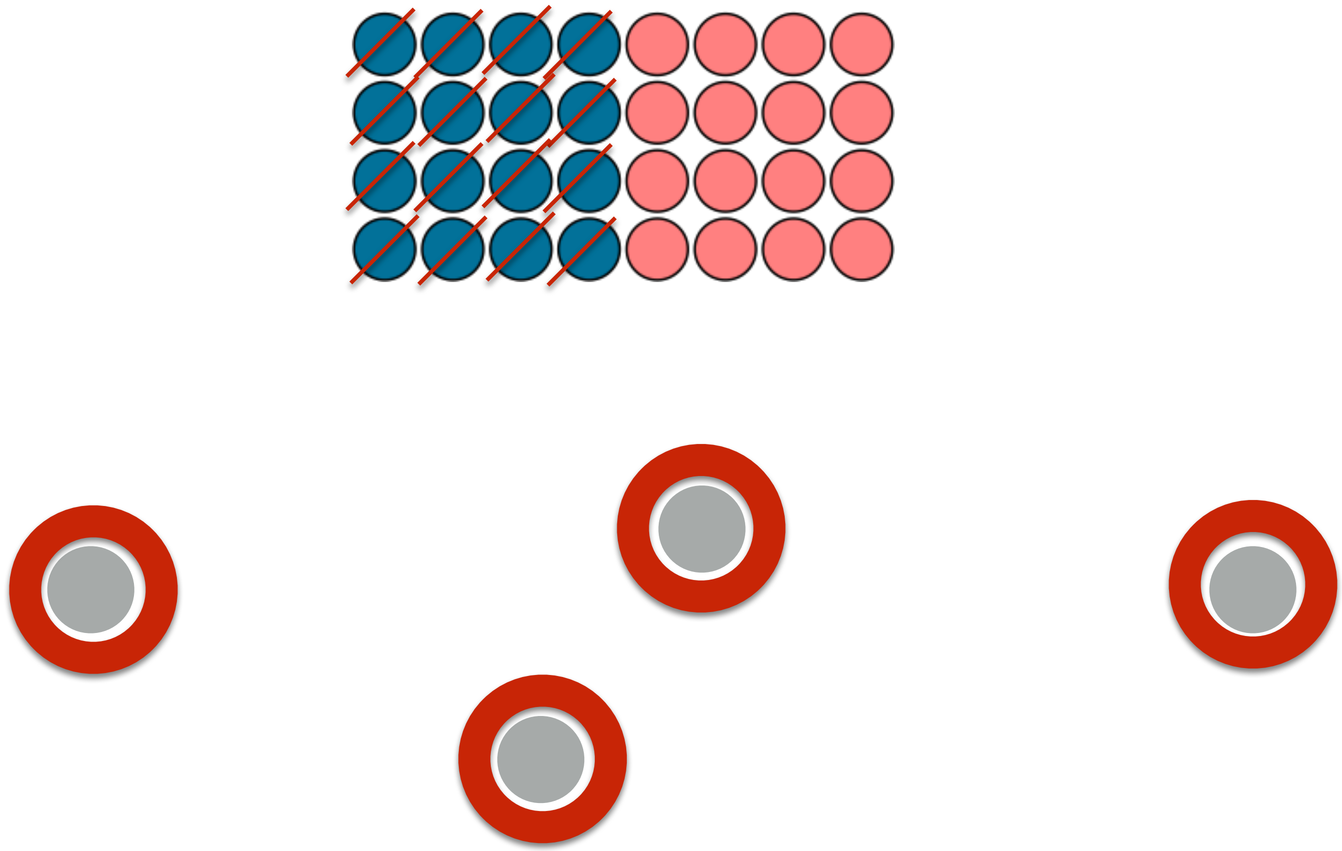




Self-interference

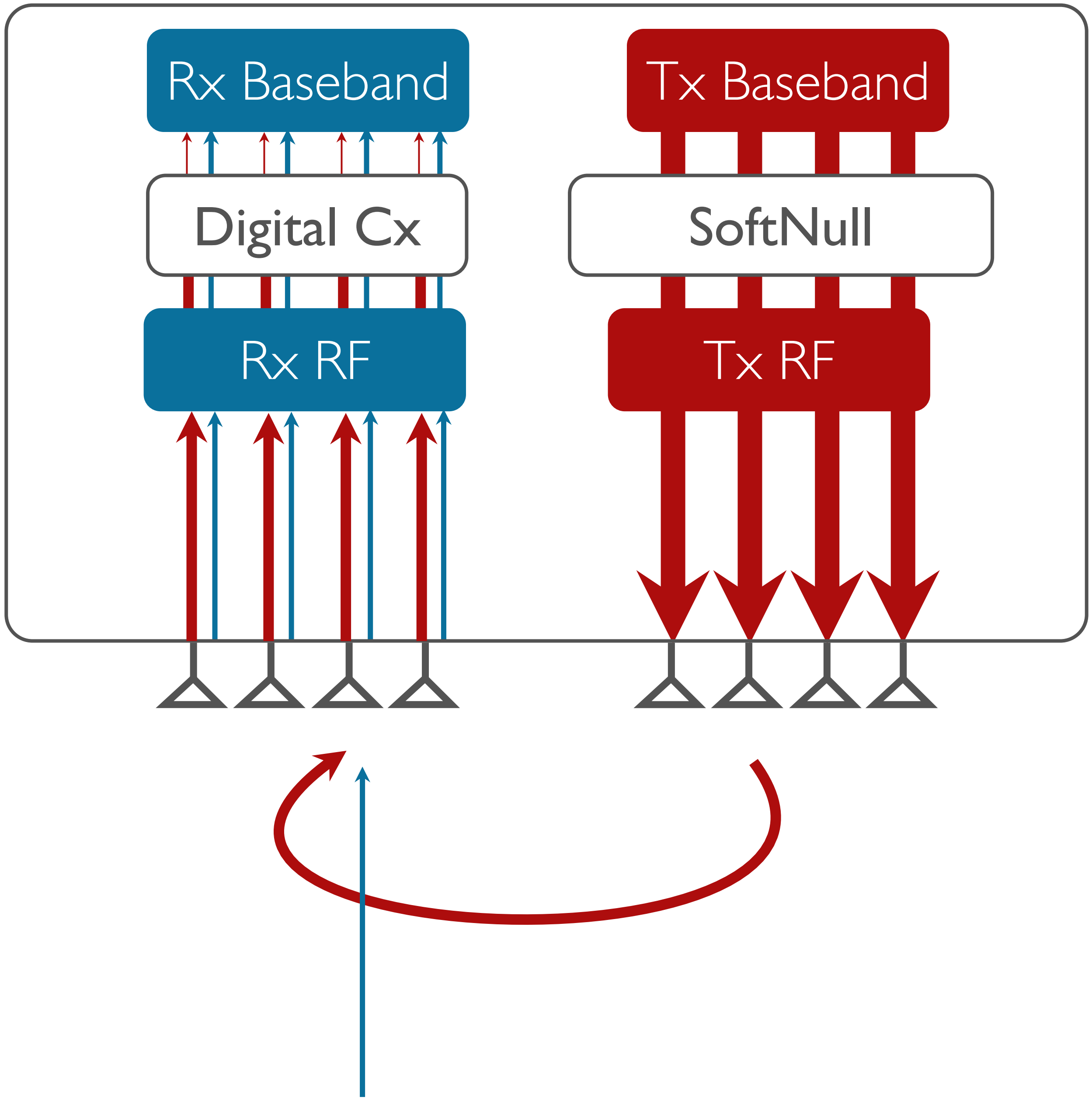
- For 2D arrays, **many direct** self-interference path
- Transmit beamforming must suppress both direct and reflected paths

Nulling is Not Possible



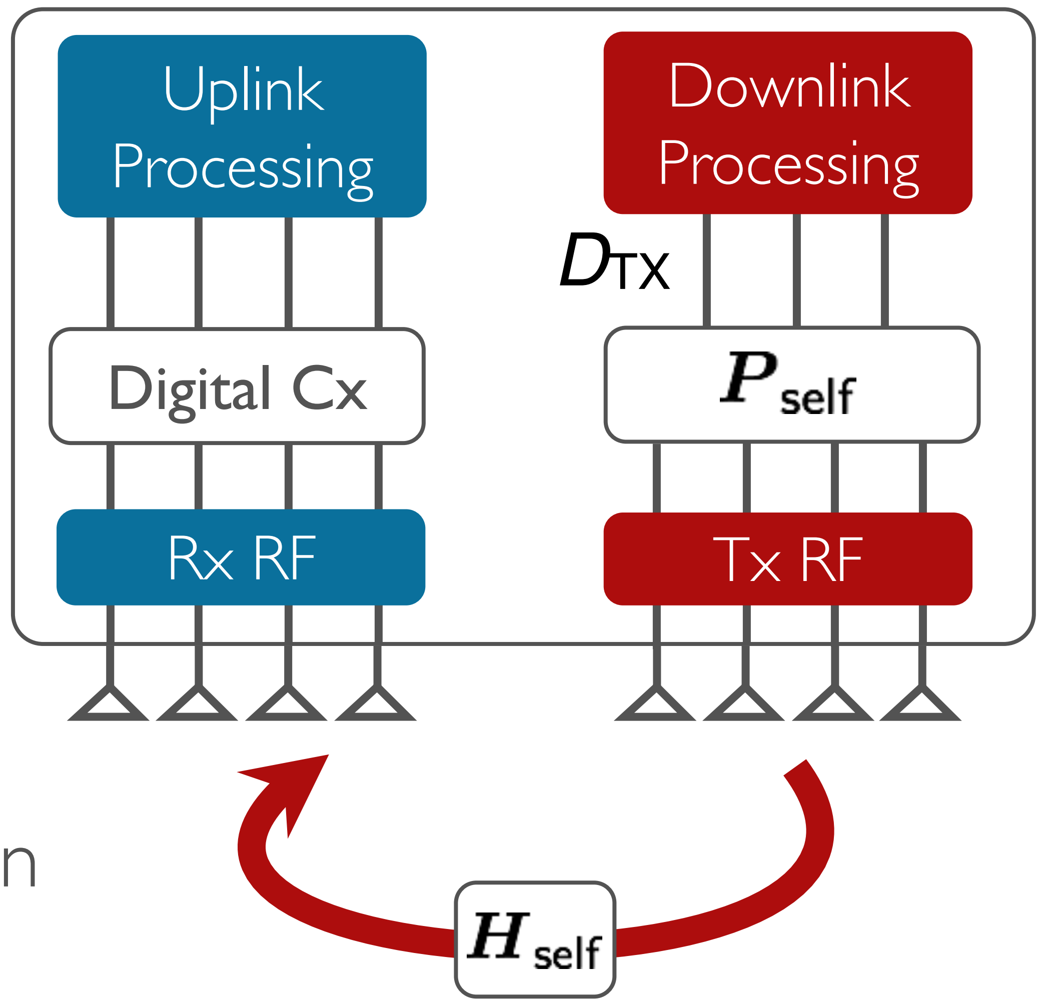
- (# of Tx antennas) − (# of Nulls) = # of Effective antennas
- More nulls means less power to each user

But we don't need to *null* self-interference?



SoftNull

- Given a required # of effective Tx antennas, D_{TX}
- Select beam-weight matrix, $\boldsymbol{P}_{\text{self}}$, which maximally suppresses self-interference
- Effective self-interference channel: $\boldsymbol{H}_{\text{self}}\boldsymbol{P}_{\text{self}}$



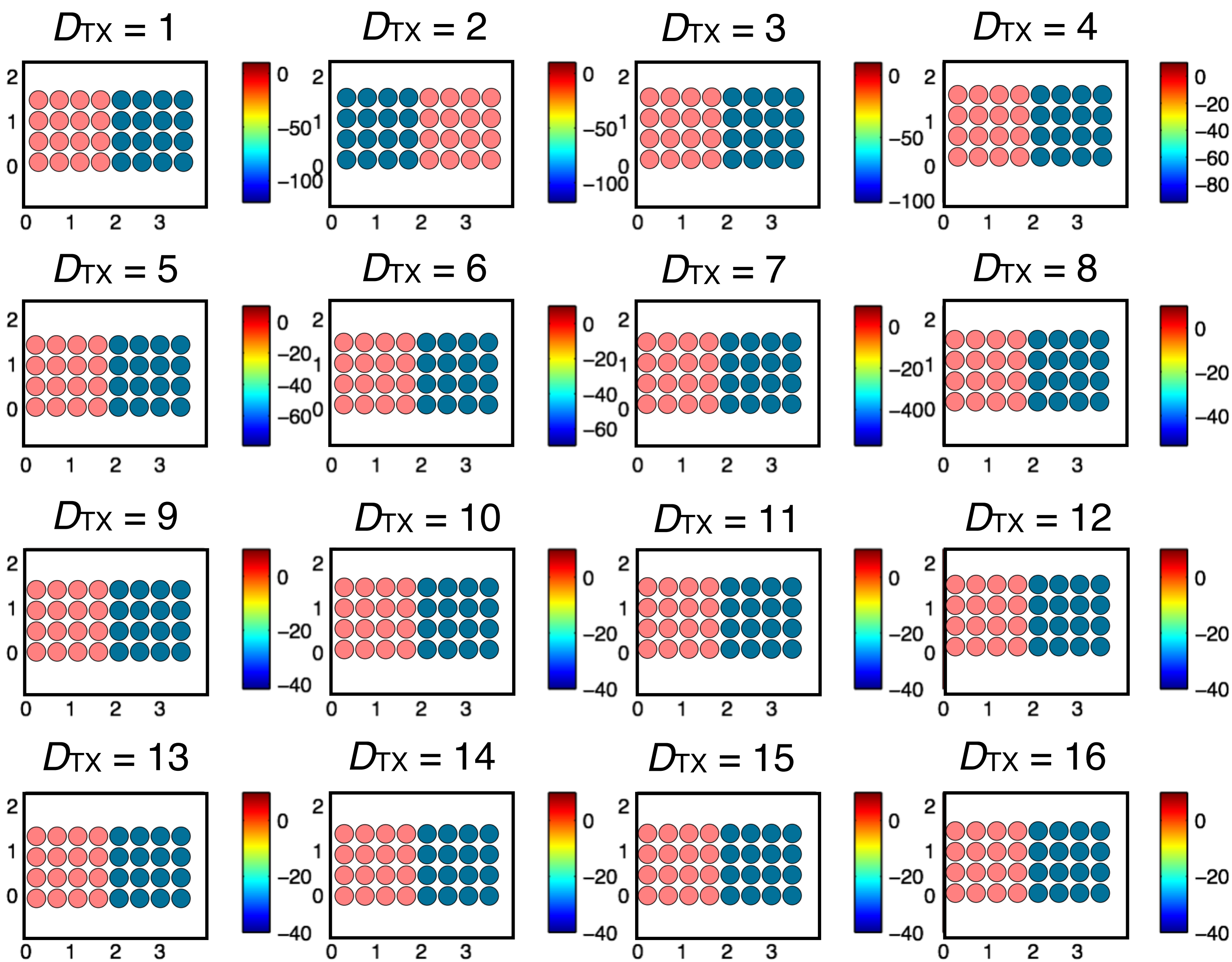
$$\boldsymbol{P}_{\text{self}} = \operatorname{argmin} \|\boldsymbol{H}_{\text{self}}\boldsymbol{P}_{\text{self}}\|_F,$$

$$\text{s.t. } \boldsymbol{P}_{\text{self}}^{\mathrm{H}}\boldsymbol{P}_{\text{self}} = \boldsymbol{I}_{D_{\mathrm{TX}} \times D_{\mathrm{TX}}}$$

Simple closed form solution

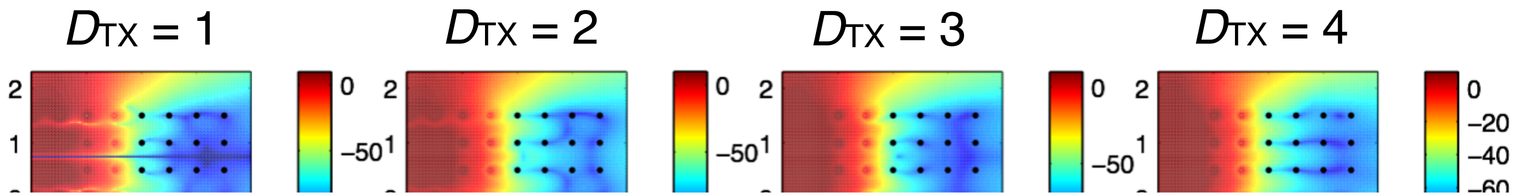
SoftNull example:

Self-interference power vs. # of effective Tx antennas, D_{TX}



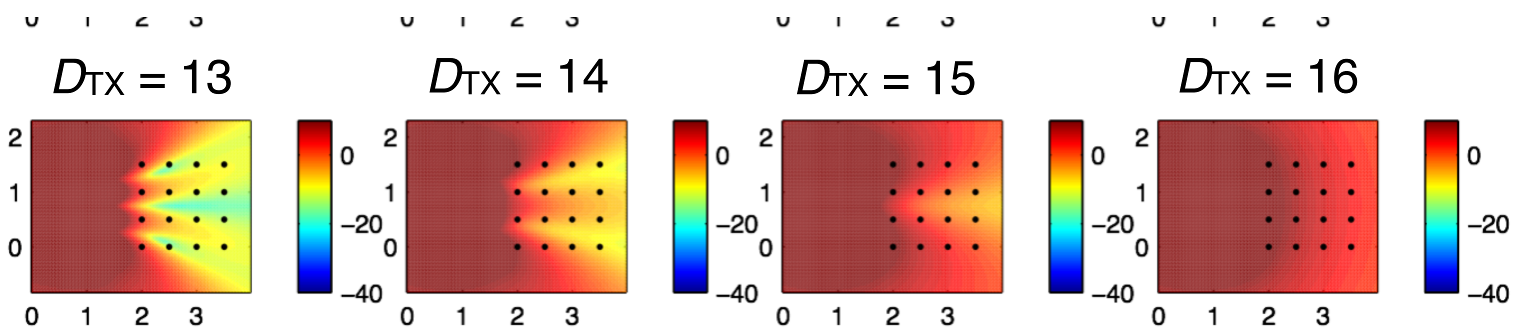
SoftNull example:

Self-interference power vs. # of effective Tx antennas, D_{TX}



SoftNull tradeoff

- As # of effective antennas decreases:
  - Uplink benefits from better self-interference suppression
  - Downlink suffers due to lower SNR

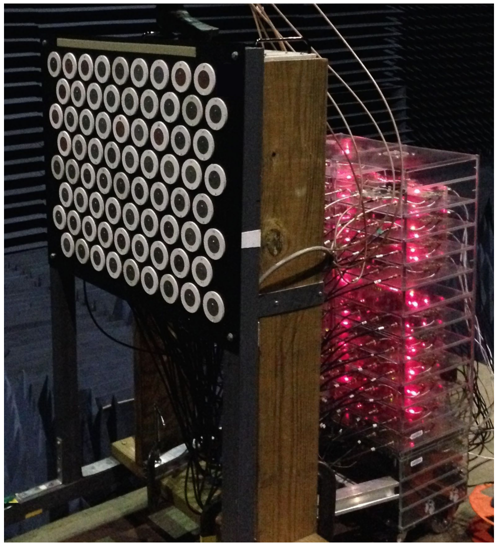


SoftNull Feasibility Study

- Is a “good” SoftNull tradeoff feasible for real channels?
  - Impact of array partitioning
  - Impact of backscattering

- Is benefit to uplink SoftNull worth the cost to the downlink?

Argos-based Measurement Platform



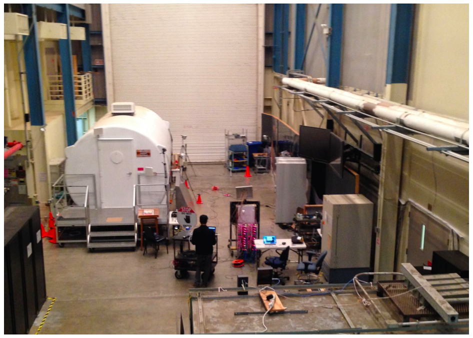
- NASA Array+Argos Base Station
  - 72 patch antennas, 8x9 grid
  - 18 WARP nodes
- 4 Users via WARP Measure 72 X 72 self-coupling channel
- OFDM pilots from each antenna while all others listen
  - Enables comparison of arbitrary Tx/Rx partitions
  - Measure 72x4 uplink and 4x72 downlink channel

Measurement Campaign: 3 Environments

Anechoic Chamber

Outdoor

Indoor



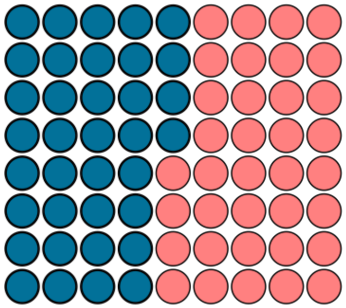
SoftNull Feasibility Study

- Is a "good" SoftNull tradeoff feasible for real channels?
  - **Impact of array partitioning**
  - Impact of backscattering

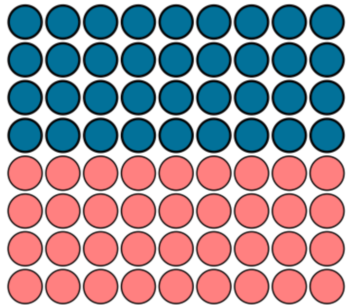
- Is benefit to uplink worth the cost to the downlink?

Tx/Rx Partitioning

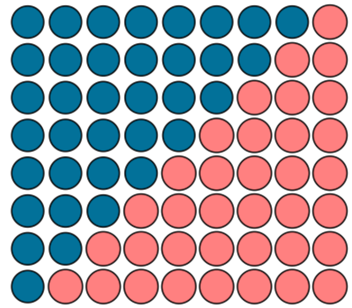
East-West



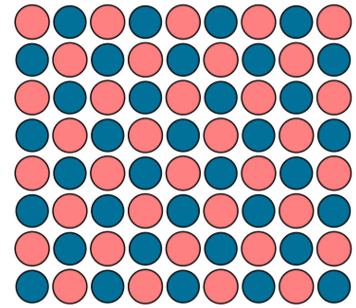
North-South



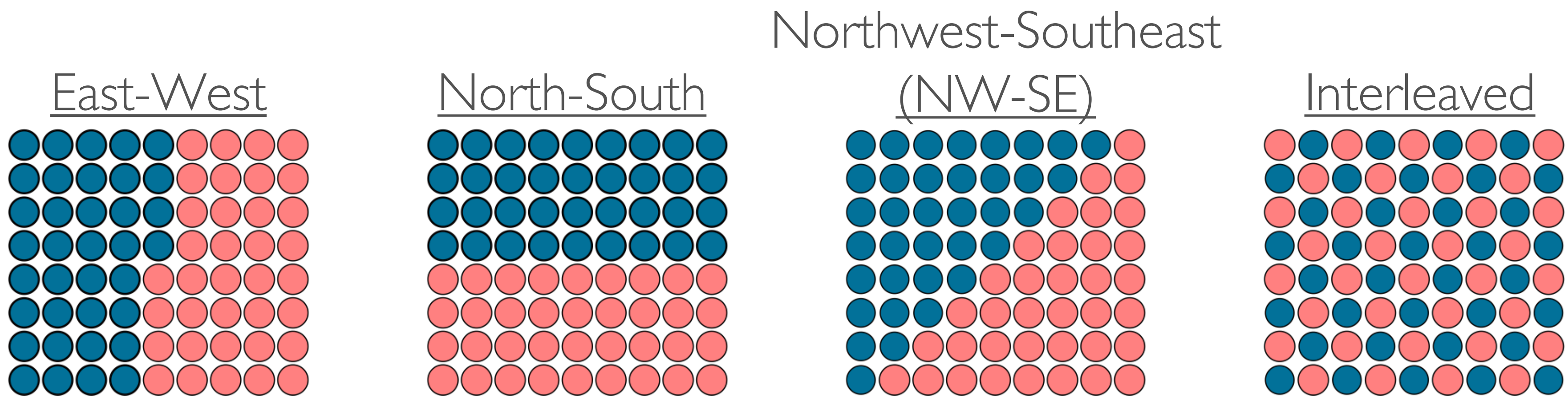
Northwest-Southeast
(NW-SE)

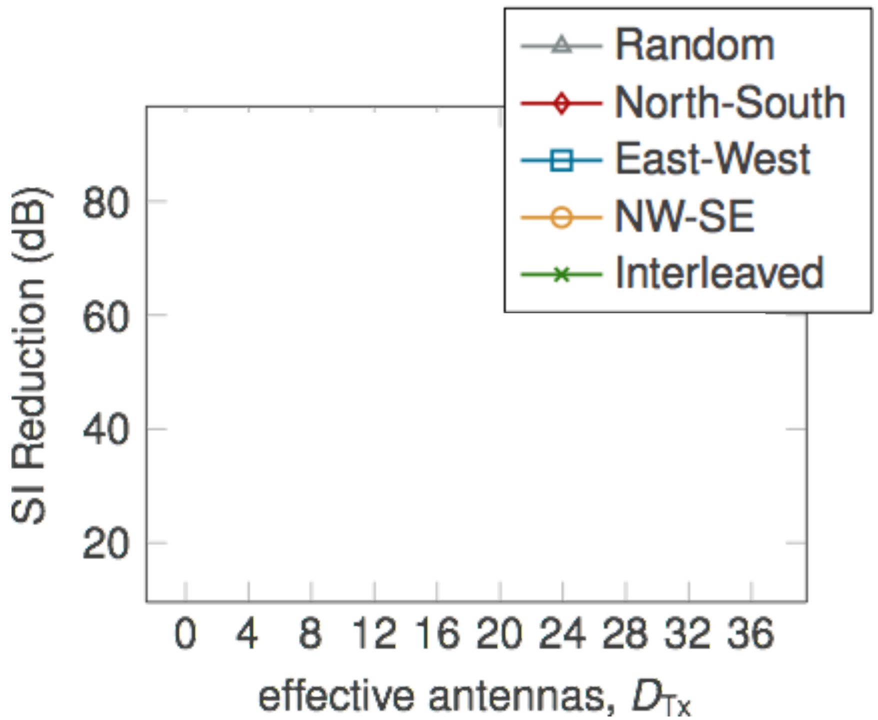


Interleaved



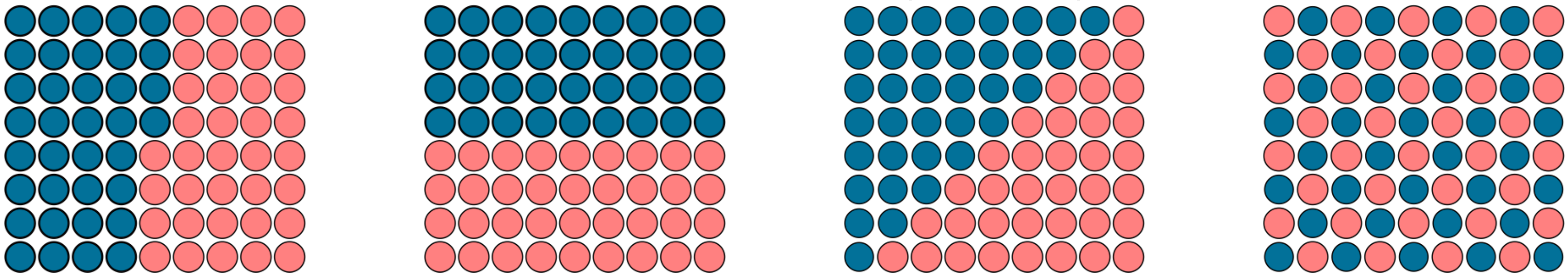
Tx/Rx Partitioning Results (Anechoic Chamber)

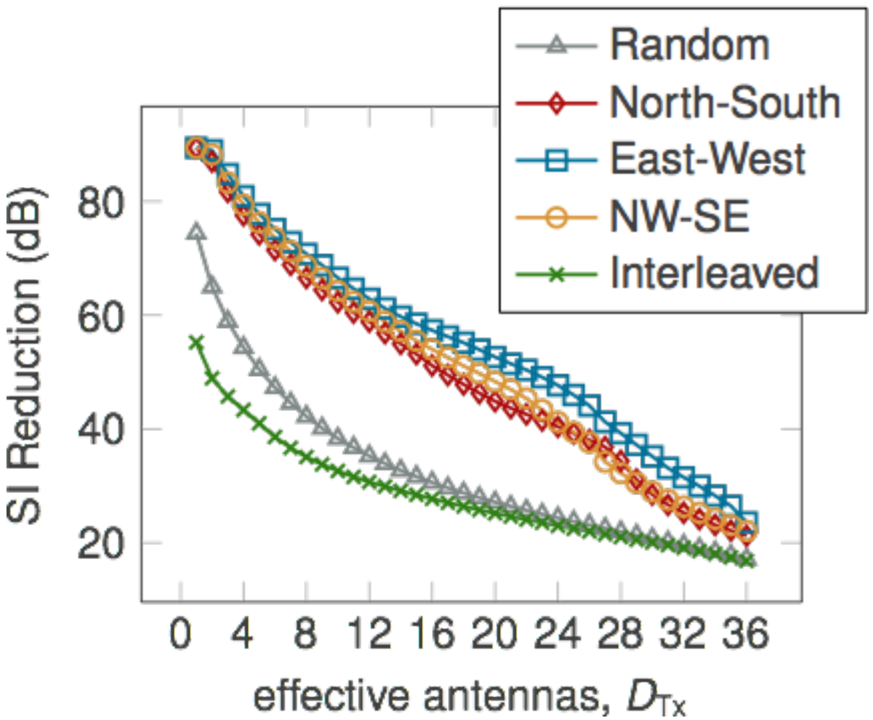




Tx/Rx Partitioning Results (Anechoic Chamber)

East-West | North-South | Northwest-Southeast (NW-SE) | Interleaved





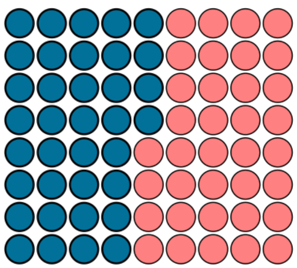
- Contiguous splits are best
- Minimizes angular spread of the self-interference

SoftNull Feasibility Study

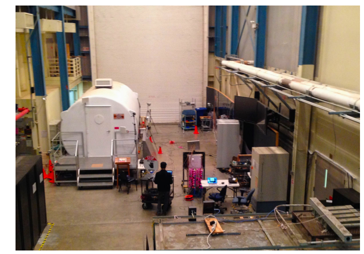
- Is a “good” tradeoff feasible for real channels?
  - Impact of array partitioning
  - **Impact of backscattering**
- Is benefit to uplink worth the cost to the downlink?

Impact of Back-scattering

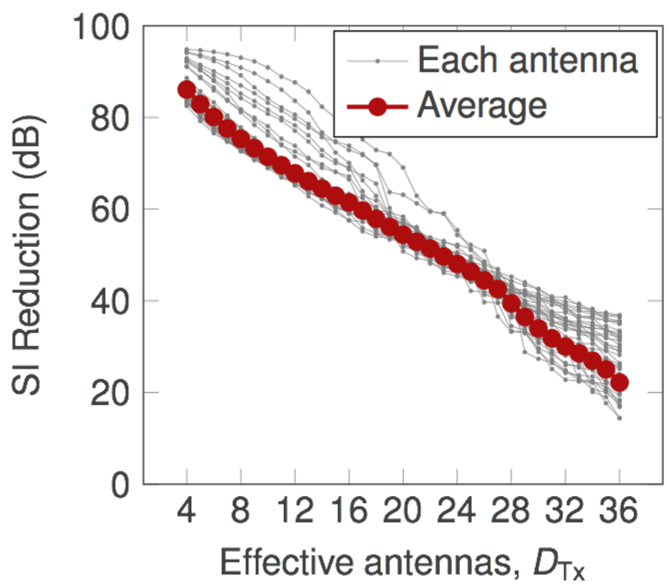
East-West

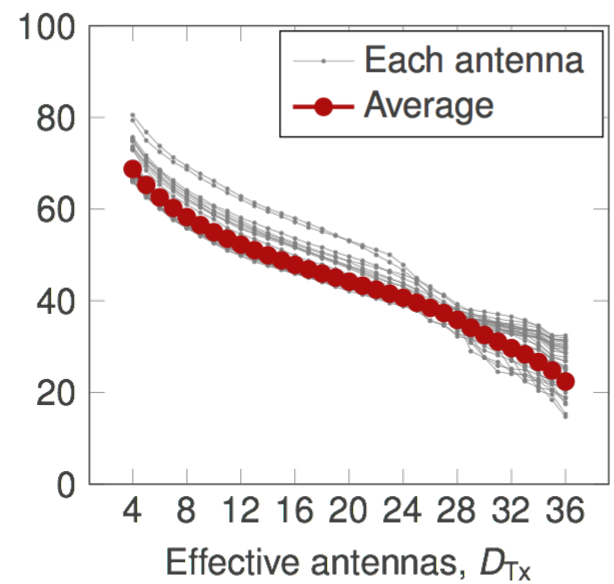


Outdoor



Indoor





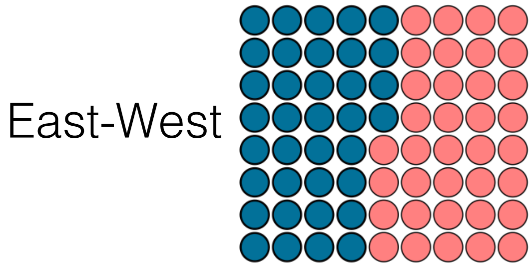
- More backscattering leads to less suppression (as theory predicts)
- Reason: backscatter breaks antenna correlation

SoftNull Feasibility Study

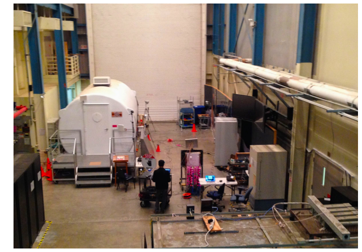
- Is a "good" tradeoff feasible for real channels?
  - Impact of array partitioning
  - Impact of backscattering

- **Is benefit to uplink worth the cost to the downlink?**

Is Benefit to Uplink Worth the Cost to the Downlink?



Outdoor



Indoor

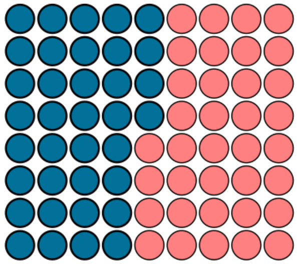
- Scenario: East-West split, indoor and outdoor
- Methodology: simulation using real measured channels
- Compare uplink and downlink rates of SoftNull versus half duplex and ideal full-duplex

Simulation Parameters

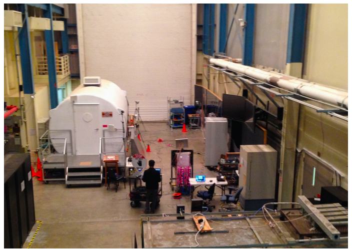
Base station power	0 dBm
Mobile user power	-10d Bm
Noise power	-95 dBm
Dynamic range limit	25 dB
Number of users	**4**
Path Loss	**85 dB (300m)**

Is benefit worth the loss in downlink SNR?

East-West

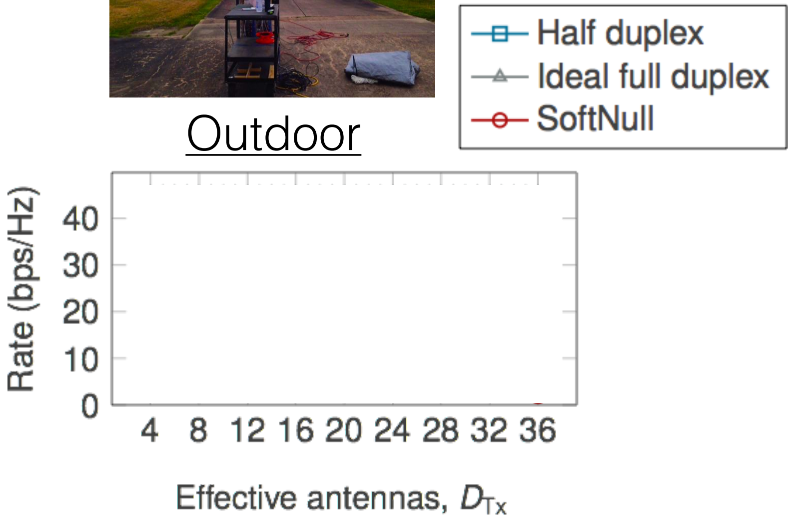


Outdoor



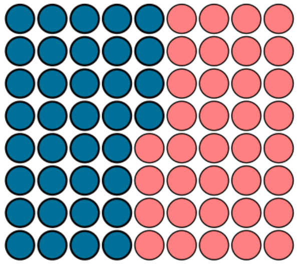
Indoor

Uplink:

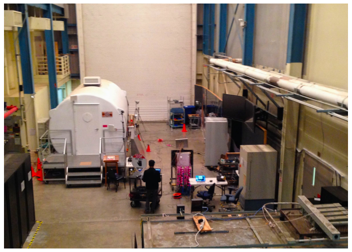


Is benefit worth the loss in downlink SNR?

East-West

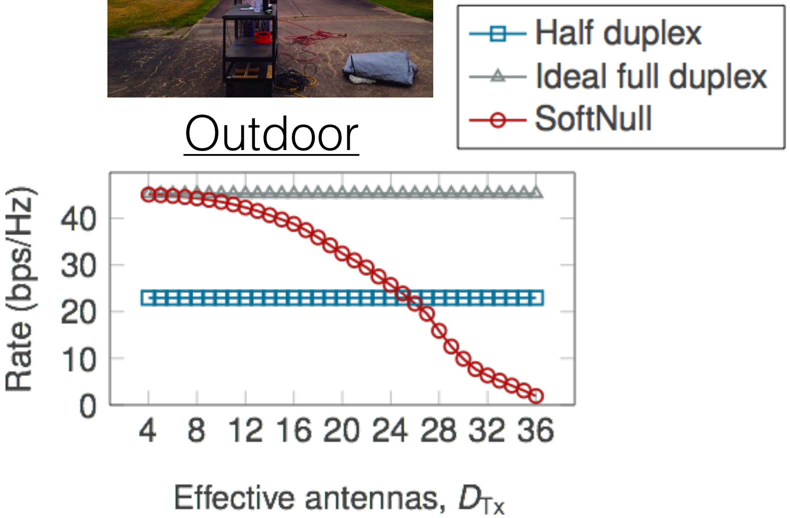


Outdoor



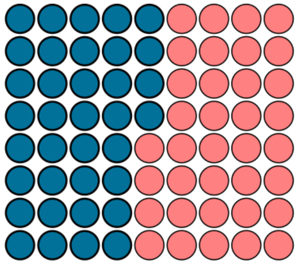
Indoor

Uplink:

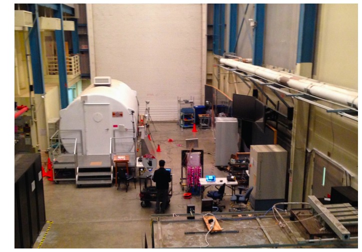


Is benefit worth the loss in downlink SNR?

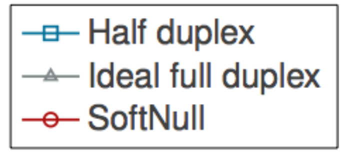
East-West



Outdoor

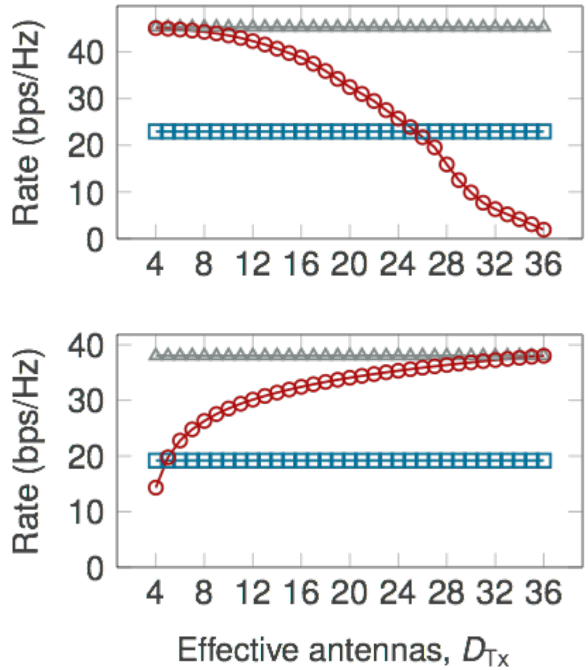


Indoor



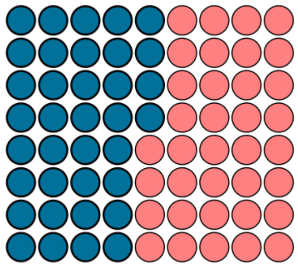
Uplink:

Downlink:

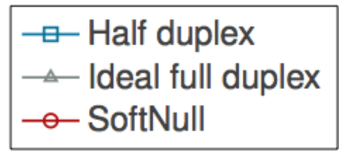


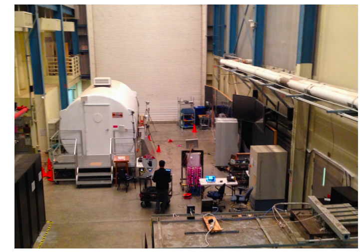
Is benefit worth the loss in downlink SNR?

East-West



Outdoor



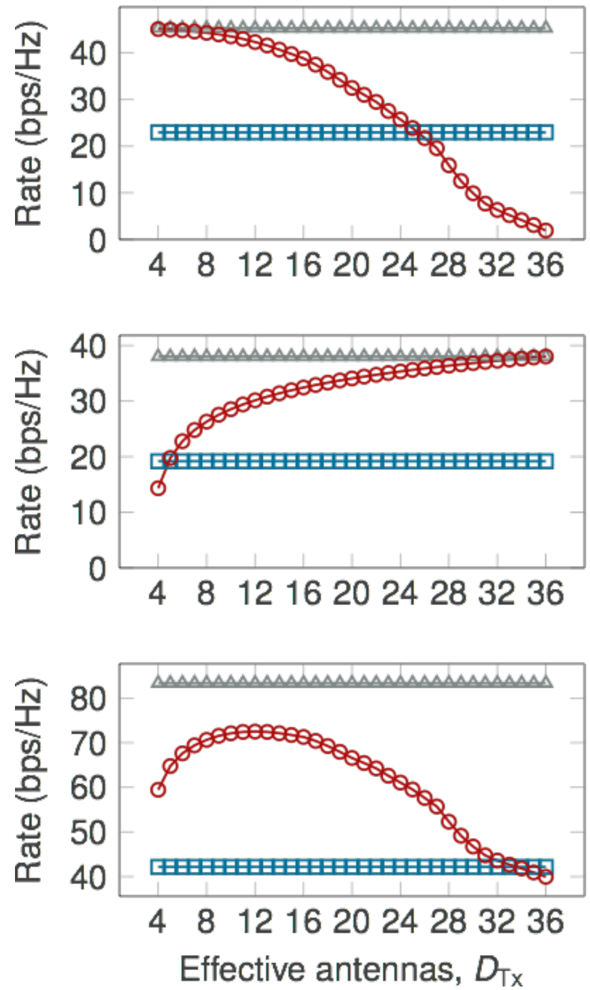


Indoor

Uplink:

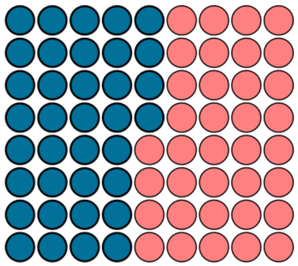
Downlink:

Uplink+Downlink:

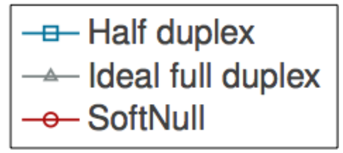


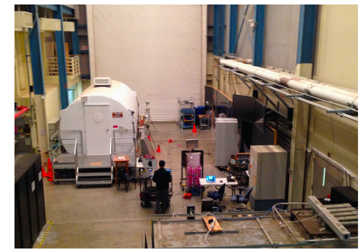
Is benefit worth the loss in downlink SNR?

East-West



Outdoor



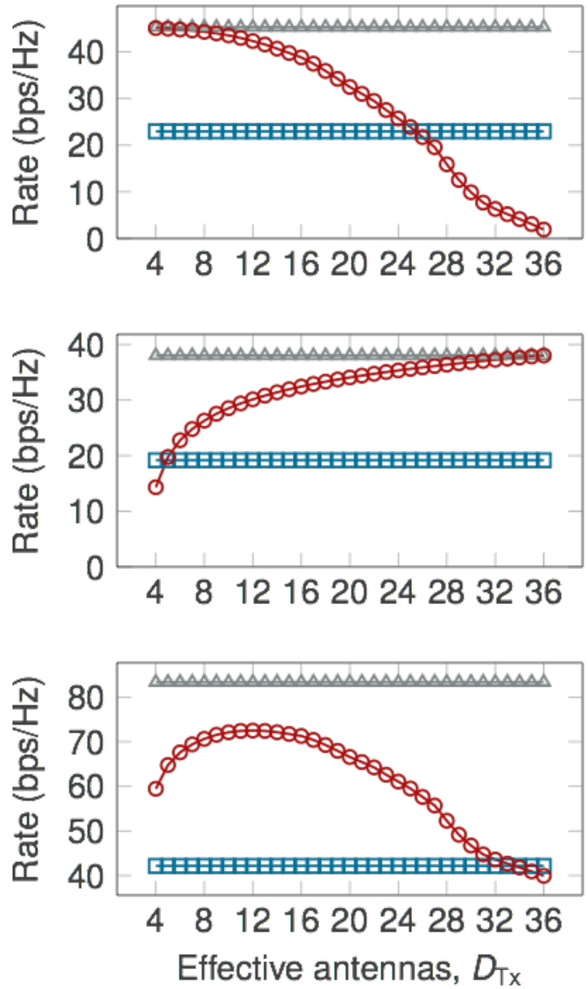


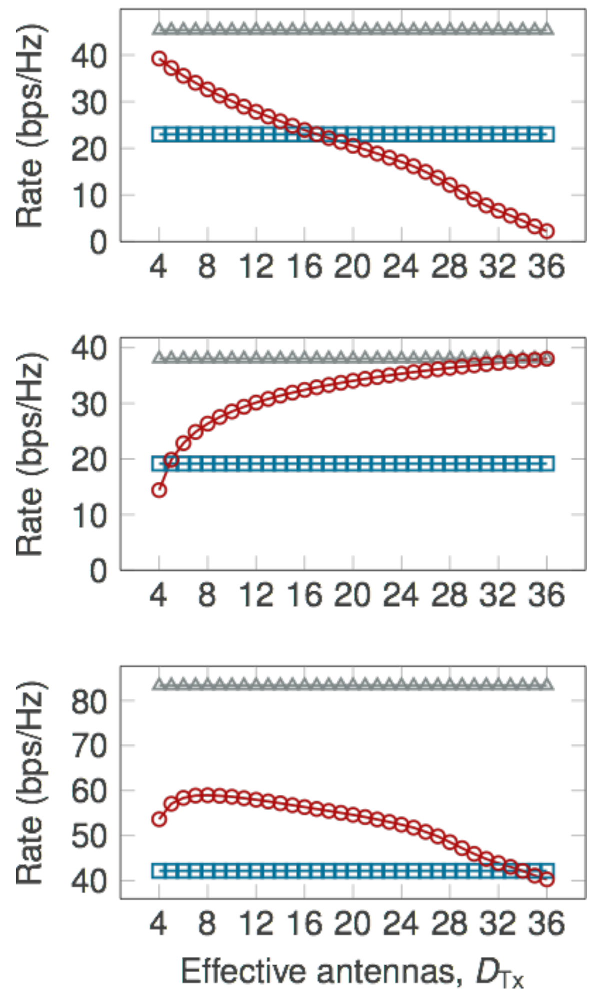
Indoor

Uplink:

Downlink:

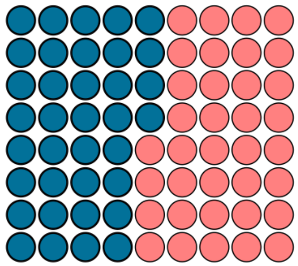
Uplink+Downlink:





Impact of distance (i.e. path loss)

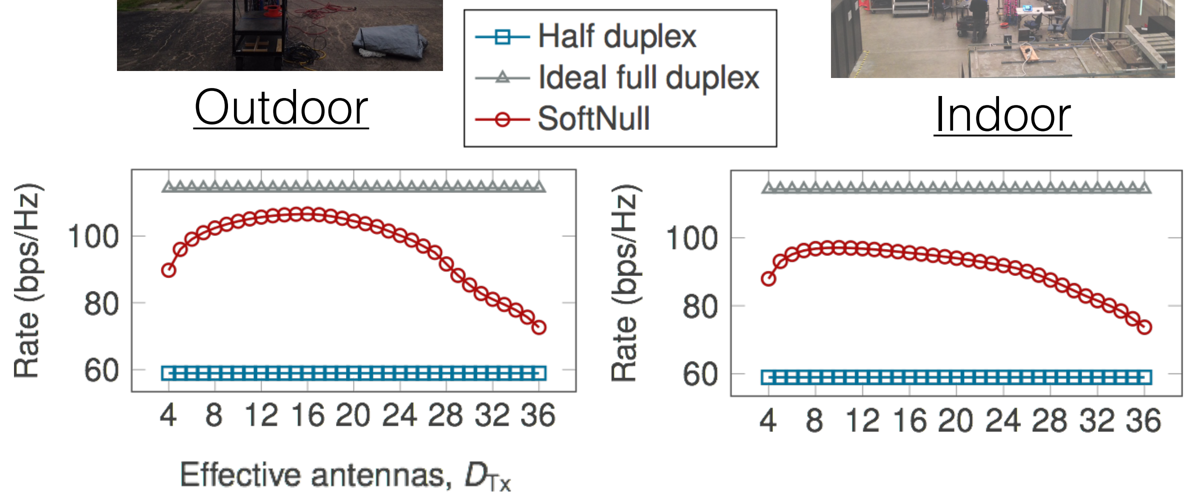
East-West



Outdoor

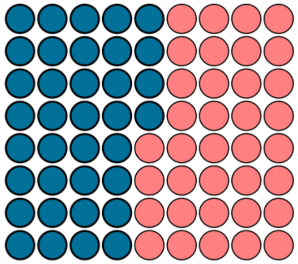
Indoor

70 dB path loss
(50m LoS)

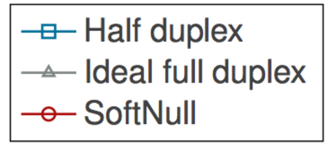


Impact of distance (i.e. path loss)

East-West



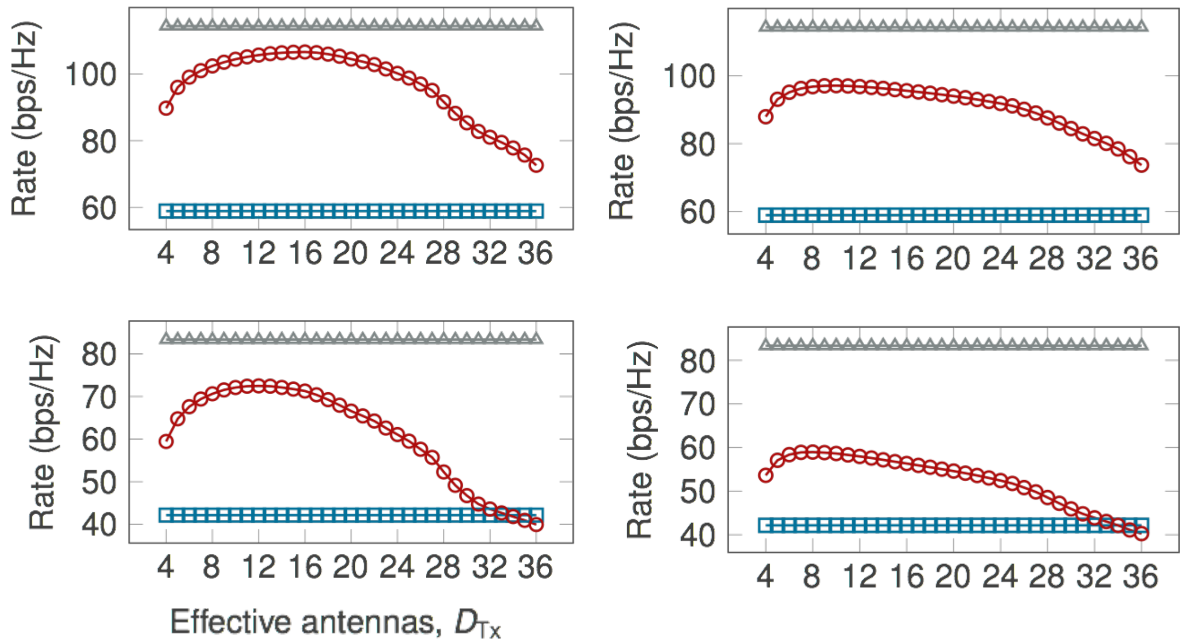
Outdoor



Indoor

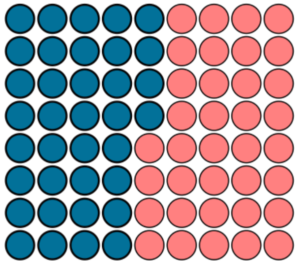
70 dB path loss
(50m LoS)

85 dB path loss
(300m LoS)



Impact of distance (i.e. path loss)

East-West



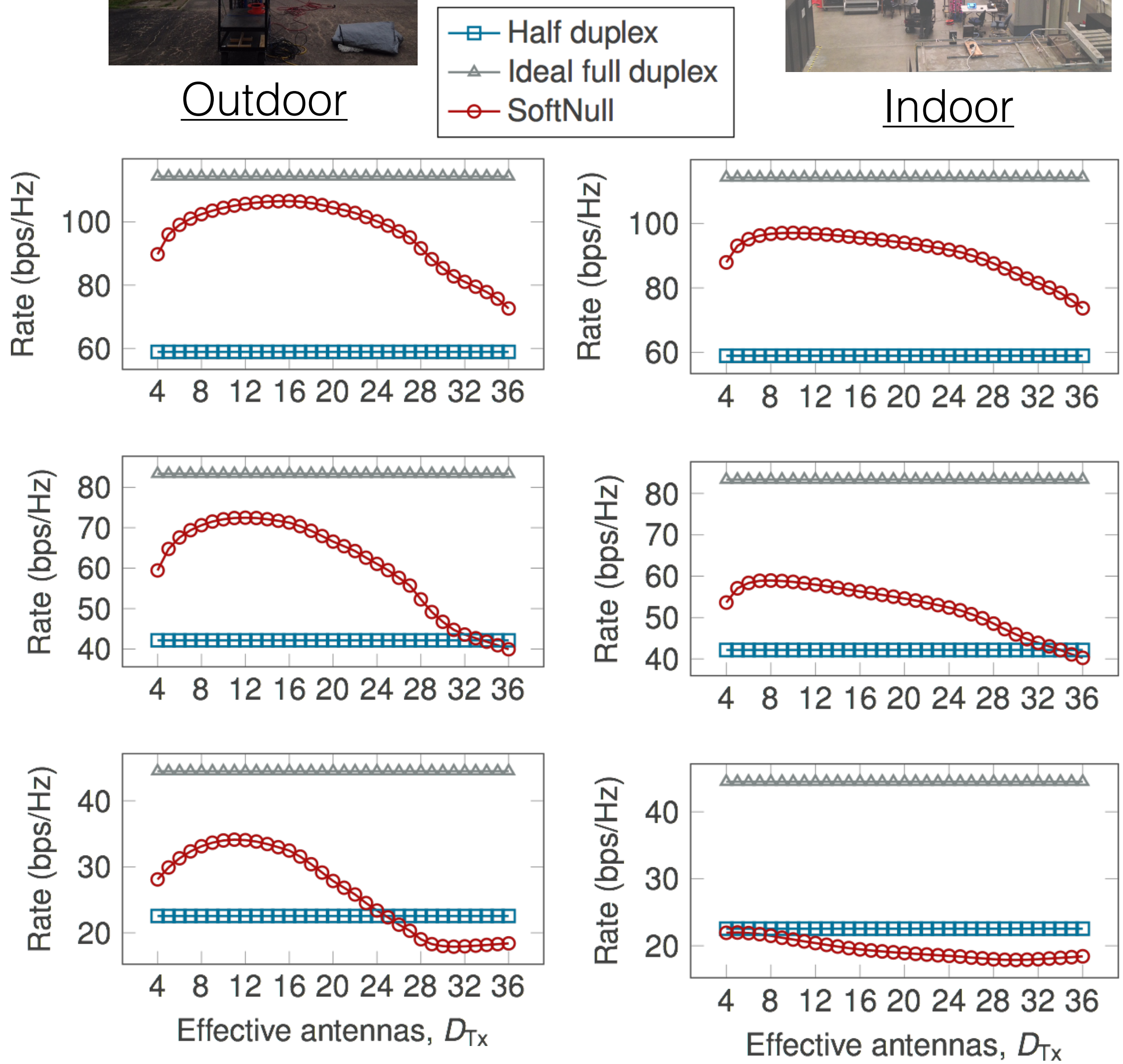
Outdoor

Indoor

70 dB path loss
(50m LoS)

85 dB path loss
(300m LoS)

100 dB path loss
(1km LoS)

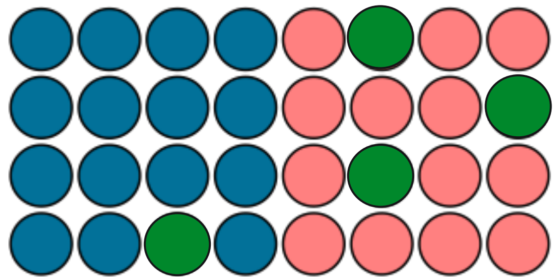


SoftNull Feasibility Study

- **Is a "good" tradeoff feasible for real channels?**
  - Yes, when array partitioned contiguously
  - Especially in low-backscattering deployments (like on base-stations)

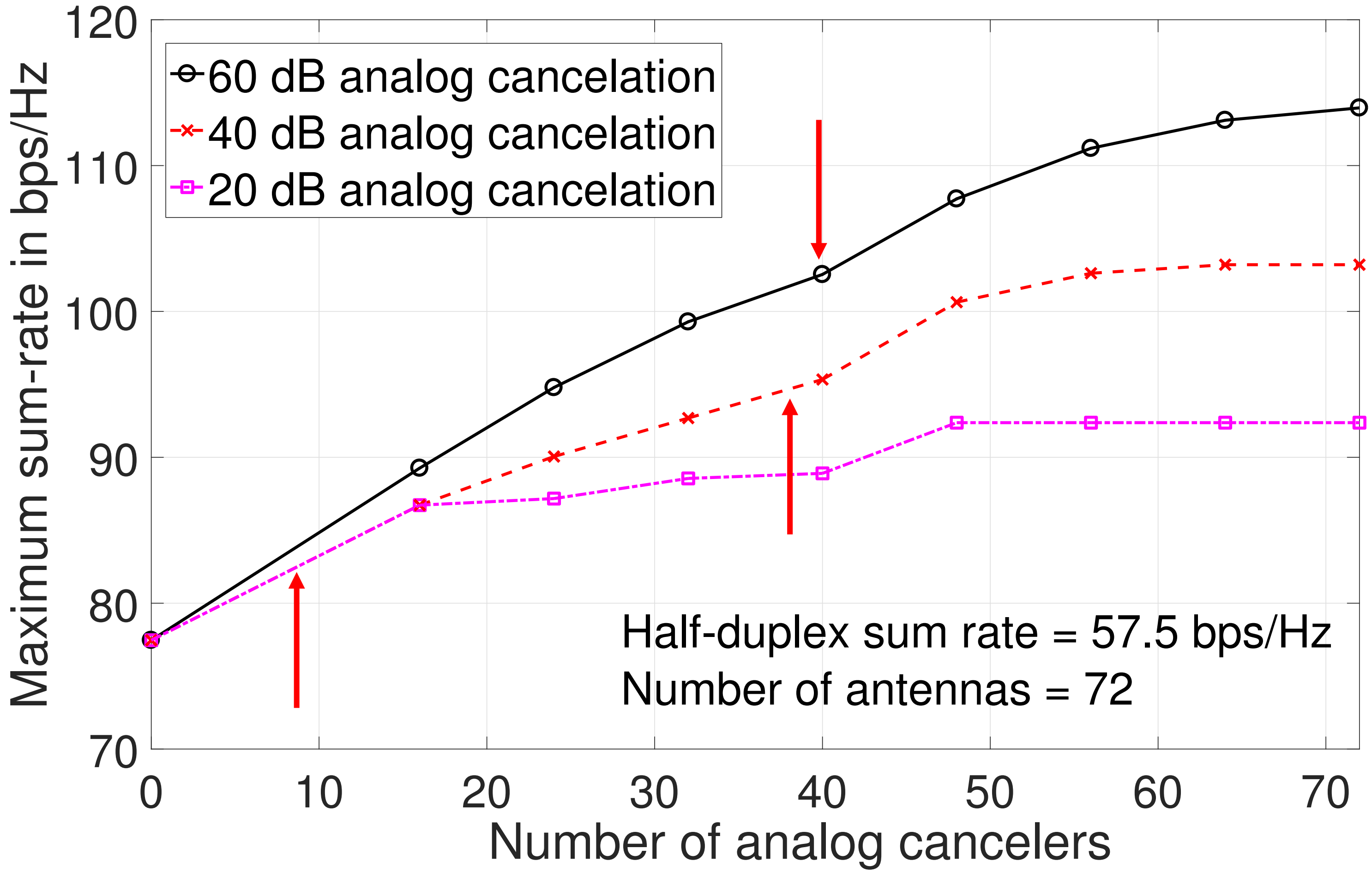
- **Is benefit to uplink worth the cost to the downlink?**
  - Yes, for low to medium path losses
  - Especially when # of antennas >> # number of users

JointNull: A Small # of Analog Cancellers



- Add a small number of analog cancellers, that can make any antenna full-duplex
- So there are three parts to overall cancellation
  - Transmit pre-coding
  - Analog cancellation
  - Digital cancellation
- Sum-rate maximizing antenna configuration & precoding

JointNull: A Small # of Analog Cancellers

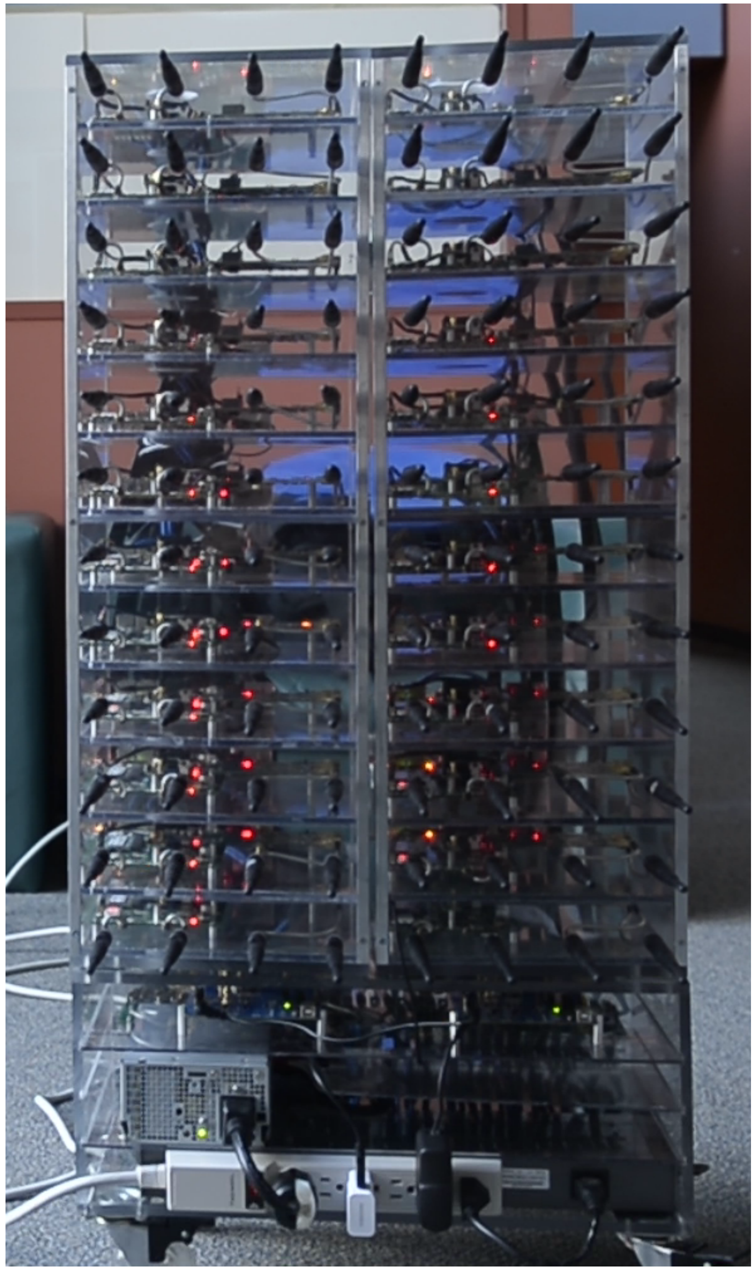


- If analog cancellers are low-quality, ~M/10 achieve 90% of max sum-rate
- If higher quality, need ~M/2 cancellers to achieve 90%

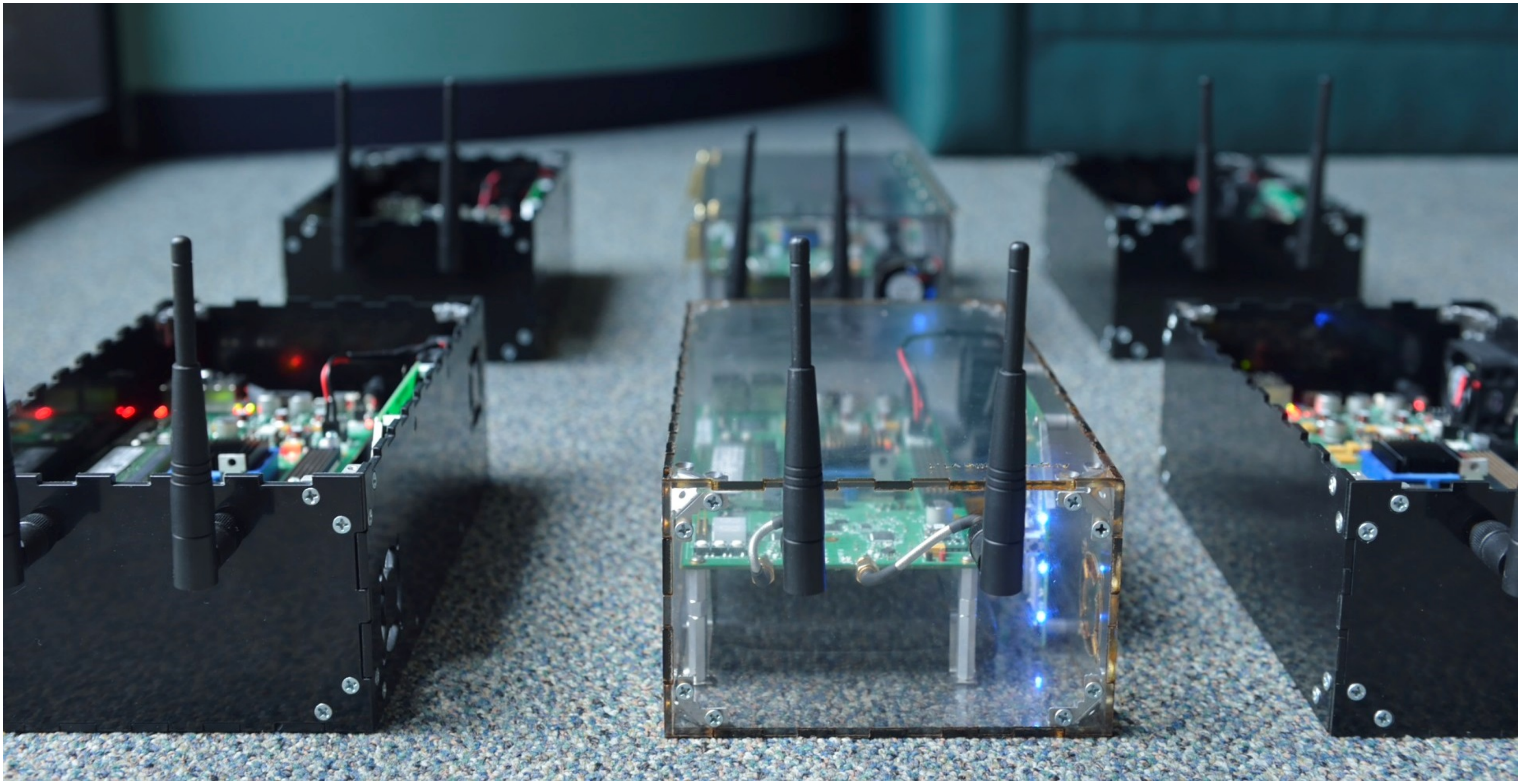
Conclusions

- Massive MIMO means many more transmit dimensions
  - SoftNull uses it for **all-digital full-duplex**
  - **No new analog components – build on today's radios**
  - JointNull generalizes it **partial-analog full-duplex**
- **Platform crucial**
  - Have real-time implementation & evaluation of SoftNull
  - Real-time results closely match today's results

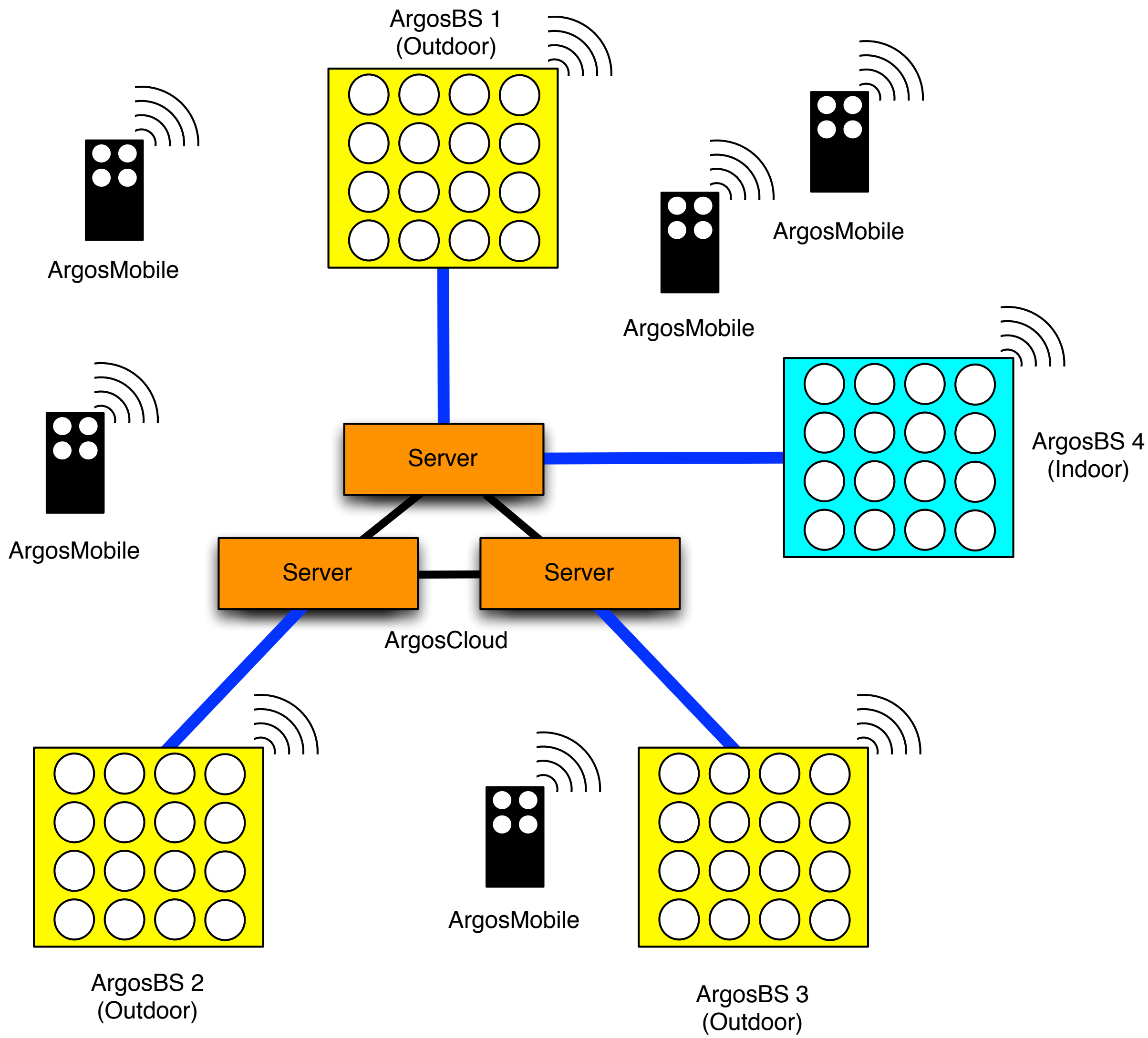
Rice Argos V2: 96 Antennas (Scalable to 144 Antennas)



ArgosMobile



ArgosNet: Total of 400 Radios



NSF CRI 2014-2017: **ArgosNet** by Zhong, Knightly and Sabharwal

Questions or Comments ?

Full-duplex: http://fullduplex.rice.edu

WARP: http://warp.rice.edu

Argos: http://argos.rice.edu

Scalable Health: http://sh.rice.edu